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CONCEPTUAL INVESTIGATIONS OF VARIABLE GEOMETRY SPACE STRUCTURES

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CONCEPTUAL INVESTIGATIONS OF VARIABLE GEOMETRY SPACE STRUCTURES

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Final Report

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M. Lebovits,
H. L. Sujata,
C. F. King, and
J. W. Young

May 1963
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[signature] for

R.P. Jackson, Vice President
And Assistant General Manager,
Northrop Space Laboratories

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NOTICES

FOREWORD

This final report was prepared by Northrop Space Laboratories, Hawthorne, California under NASA Contract NASr-114. The contract was administered by the Office of Advanced Research and Technology, with Mr. N. Mayer, Project Monitor.

Authors of this report are M. Lebovits, Principal Investigator, H. L. Sujata, C. F. King, J. W. Young, and other members of the Structures Branch, Systems Technology Group, M. Lebovits, Chief. Other contributors include R. S. Fujioka, W. R. Hilker, K. H. Hsiao and D. R. Ulbrich.

ABSTRACT

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A conceptual investigation of a number of variable geometry (VG) structures was made to establish their geometric, structural, and deployment characteristics. The systems evaluated were the following rigidized VG structures: frame, panel, integrated panel and frame, and panel-sphere. The study concludes that the rigidized VG structure possesses considerable versatility and potential usefulness as a space system structure.

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SECTION I

INTRODUCTION

Man, in his conquest of space, will require the use of structures to house, protect, and deploy his various systems and vehicles. Perhaps the most familiar system is the spacecraft. Other systems which will soon follow are lunar shelters and space stations. Each of these systems will employ many different structures to perform the multitude of functions necessary to satisfy the mission requirements.

The most ideal situation would be to compress the system into an extremely small, light-weight package for transportation purposes and deploy it into the desired configuration after delivery to the desired location. The requirement for light weight and nominal launch package size will always exist because of launch vehicle constraints. Therefore, for a space structure to be efficient, it should be capable of being folded into a small package and, when desired, being deployed into the final, larger, structural system.

To accomplish this, a number of concepts have been proposed which all fit into the general category of expandable structures. The structures can be further categorized into (1) inflatables, or (2) rigid systems (Ref. 1). The inflatable is a balloon-type which is intentionally pressurized to expand to many times its initial size. The rigid expandable structure is made up of rigid components compacted into a small package which, upon signal, rearrange themselves to provide for a greater surface area or enclosed volume. Two of the more familiar systems utilizing this concept are the solar panel that deploys to an enlarged surface and the telescoping cylinder which provides an enlarged contained volume.

A system used in the space environment requires special design features. For example, protection from damage due to micrometeoroids (Ref. 2) is frequently required to protect against puncture and deflation of a pressurized system. Even in instances where deflation is not a problem, it is generally necessary to provide some micrometeoroid protection for the equipment on board the spacecraft.

Another special requirement resulting from the space environment is the need to protect the spacecraft payload from radiation damage by solar flares (Ref. 3, 4). This may be satisfied by the addition of shielding taking the form of solid, rigid material.

Therefore, it appears that the space structure which houses subsystems must be rigidized and have a finite thickness generally governed by micrometeoroid or solar radiation protection requirements. In the event that an inflatable system is used, it must be capable of rigidization to be effective in meeting these space-environmental requirements.

There are spacecraft which require structure for no other reason than to position or locate components. Such is the case of an arm which deploys a solar panel; another, the antenna. These structures do not require pressure containment and basically provide a means of obtaining orientation or deployment. The applied loads on these components will be very small. Nevertheless, the requirement for compact launch volume remains, and the structures must be capable of deployment in space.

The NSL Variable Geometry (VG) concepts are also capable of volumetric and area expansion in space. The frame-type system provides a basic structure in the form of a framework which can be adapted to the requirements of some space structures. It uses articulated rigid arches which rotate about a fixed rigid ring to provide a geometrically-varying structure. In operation the arches are deployed, locked in place, and form a rigid structural network. The panel-type system is made entirely of panels which are hinged for folding into a compact volume for subsequent deployment.

The study reported here concentrated on the VG concepts which introduce to the structural engineer, a new set of structural arrays that can be developed to form a broad spectrum of structural shapes for application in space, as well as--perhaps--for terrestrial use.

SECTION II

SUMMARY

2.1 INTRODUCTION

VG structures were studied to establish their feasibility and determine the general range of usefulness of each of several specific concepts. To this end, a substantial number of VG structures were investigated from the conceptual design viewpoint, parametric studies of deployed volume and area were made, and the overall system feasibility was established from an examination of materials, actuation and locking devices that could be employed.

2.2 CONCEPTUAL INVESTIGATIONS

The VG concept was primarily investigated from a conceptual design standpoint with a preliminary investigation made to determine the feasibility of building such systems.

The framework VG structure (Fig. 2-1), can be thought of as a fundamental unit which can function singly or as a component in a more complete structural system. This system can be integrated with panels to provide either basic micrometeoroid protection or surface area for other system requirements.

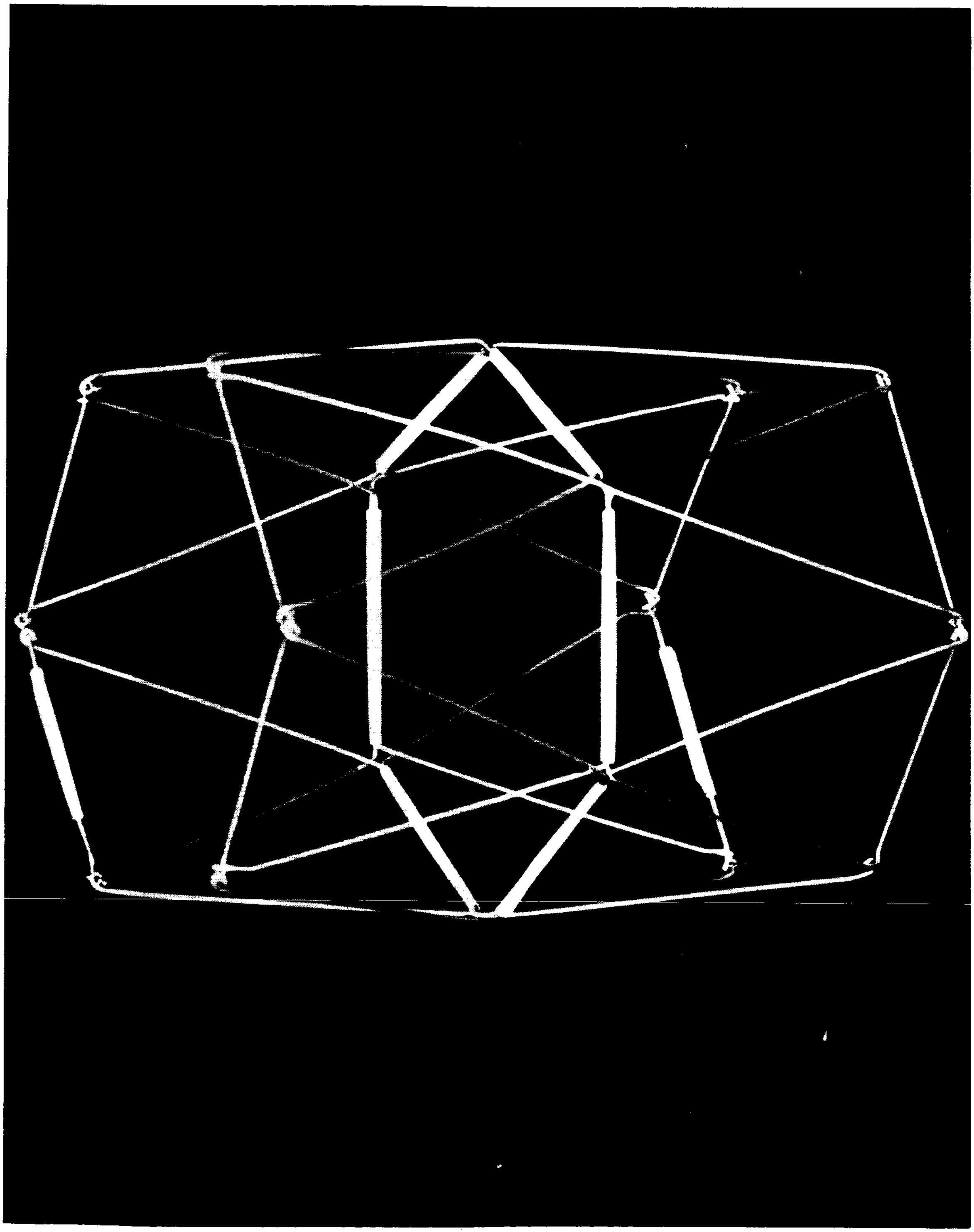


FIGURE 2-1 DEPLOYED TWO-STAGE TRAPEZOIDAL ARCH SYSTEM

Integrated panel-frames and panel structures were investigated for some of their geometric properties. Another concept, called the panel-sphere was also evaluated. The latter concept provides a number of the advantages of a panel system and provides the large volume and surface area capability of the inflatable system.

A tabulation of advantages and disadvantages for the various structures is given in Tables 2-1 and 2-2.

2.3 AREA-VOLUME PARAMETER STUDIES

Parameter studies for area and volume ratios[1] were performed for several different concepts:

a. strips

b. telescoping cylinders

c. radially expanding cylinders

d. panel-sphere

These concepts are shown schematically in Figure 2-2. The study considers an initial package which contains the compressed structure and a space volume which is considered as useable volume. It will be noted in Figure 2-2, that the compressed structure is contained with a volume

[1] The area ratio is the ratio of the deployed surface area to the original surface area; volume ratio is the ratio of the deployed to the original package volume.

TABLE 2-1
FRAME STRUCTURES

CONCEPT	ADVANTAGES	DISADVANTAGES
General	a Forms a rigid framework to resist applied loads b Large number of configurations attainable by: 1) partial deployment; 2) varying each geometry c Can be integrated with encapsulating containers to provide rigidized structure d Possesses modular features	a Framework not completely enclosed unless special techniques are used b Additional members besides basic arches and base rings required to obtain framework stability
Trapezoidal & Triangular Arches	a Forms triangulated space framework b Volume & area development limited by package size only c Arches can be curved to obtain dome structure d Readily integrated w/panels	a Maximum volume development requires large diameter
Semi-circular Arch	a Forms domed (hemispherical) shape b Arches can be curved to obtain greater dome curvature	a Limited volume expansion b Framework not triangulated; bending will occur c Not readily integrated w/panels
Interlacing Arches	a Increased member stiffness because of lateral support b Few actuators for deployment. (Could be as few as one) c Can be enclosed with panels	a Increased frictional resistance b Increased probability of cold welding
Non-Interlacing Arches	a Lower frictional loads b Less severe enclosure problems	a Less stable b More locking devices c Large number of actuators required

TABLE 2-2
PANEL STRUCTURES

CONCEPT	ADVANTAGES	DISADVANTAGES
General	a Readily integrable with other structures b Provides rigid surface for 1) micro-meteroid protection; 2) solar panels; 3) structure c Constructed terrestrially	a Relatively large package required b Relatively heavy c Large & long hinges req'd d Special sealing req'd for pressure containment
Strips	a Provides best deployed surface area	a No associated volume enclosed
Telescoping Cylinder	a Gives good surface area & volume development	a Sealing problems at joints
Expanding Cylinder	a Gives good surface area & volume development	a Sealing problem at joints
Panel-Sphere	a Nearly the entire structure can be fabricated from fiberglass which has a very favorable weight/strength ratio b The honeycomb core can be used to give lateral support to the relatively thin face sheets, thus greatly increasing the shear allowable for large thin panels c All fabrication takes place on the earth under ideal manufacturing conditions d It is quite possible that the entire structure can be converted into a monolithic shell at erection through the use of encapsulated epoxies and catalysts at the mating joints to transfer shear along the meridians and parallels e All enclosure material and pursing cables become working structure in the expanded configuration f The honeycomb panels become meteroid resistant when filled with an elastomeric material	a The system rigging and deployment hose provide an additional reliability hazard b Simulation and proof of deploy-reliability becomes difficult c The total length of hinges and mating joints which require sealing for environmental control is relative large d Segment alignment and pursing at deployment could be a problem

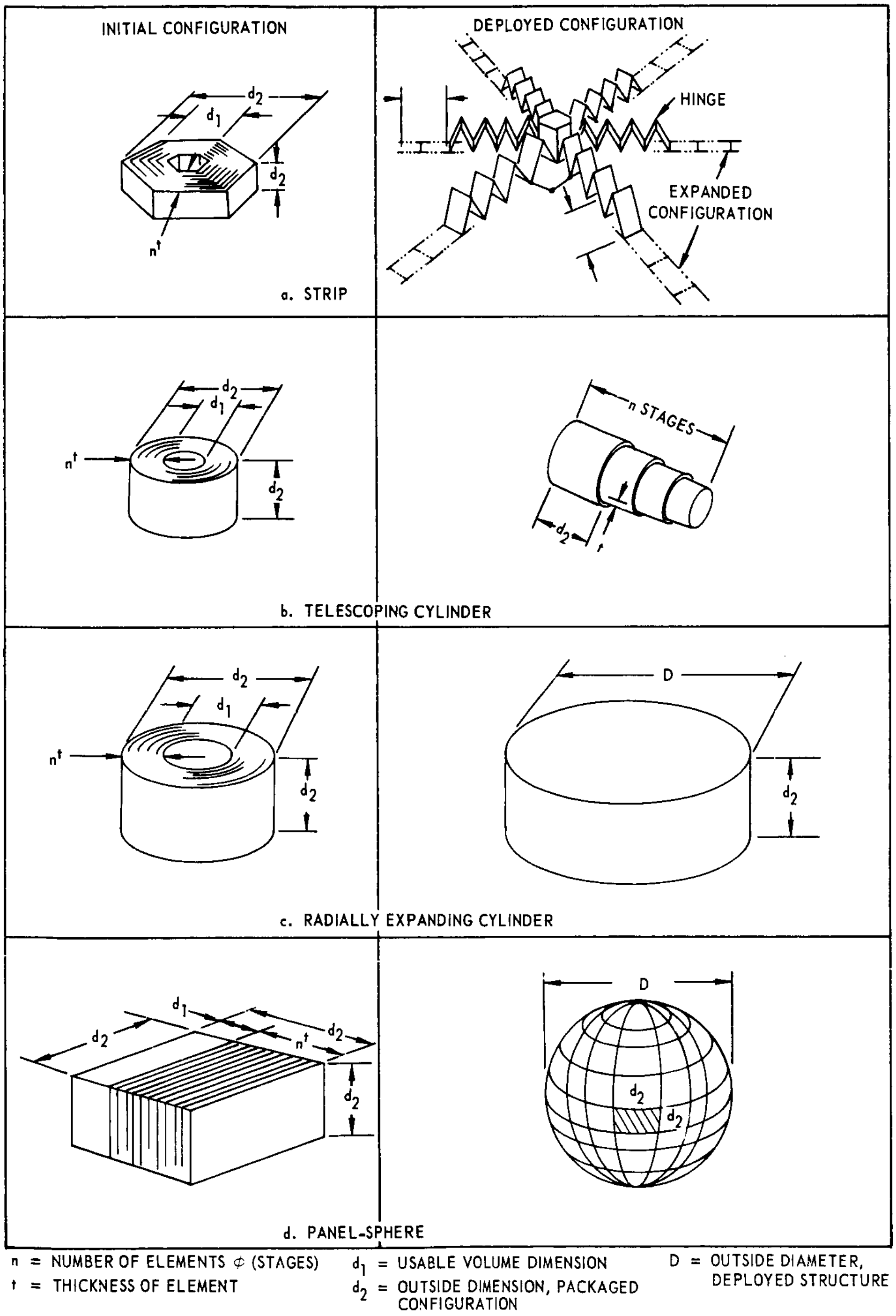


FIGURE 2-2 EVALUATED CONCEPTS FOR AREA-VOLUME PARAMETER

with an overall thickness given as (d_2-d_1), d_2 being the outside dimension, d_1 being the dimension of the useable volume. This volume may be used for the actuation or deployment devices or other equipment.

Figures 2-3 and 2-4 show the area and volume ratios for several of these concepts from which significant comparisons can be made. For example, the best method of obtaining deployed surface area is by means of the strip concept. Telescoping and radially expanding cylinders are essentially the same if all of the compacted material is used for the tubular surface; i.e., excluding end areas. The panel sphere is the least effective for area development.

The volume ratios have been found to be the greatest in those concepts which use the radially expanding cylinder. The panel sphere and the telescoping cylinder have regimimes where one or the other design may be better. The strip does not provide any additional volume in the expanded condition.

The axially-expanding frame VG structure is the same as the telescoping cylinder and will yield the same enclosed volume and surface area development.

2.4 MATERIALS, ACTUATION DEVICES, AND LOCKING DEVICES

A preliminary evaluation of the materials, actuation devices, and locking devices which would be used in a VG structure was included in the investigation.

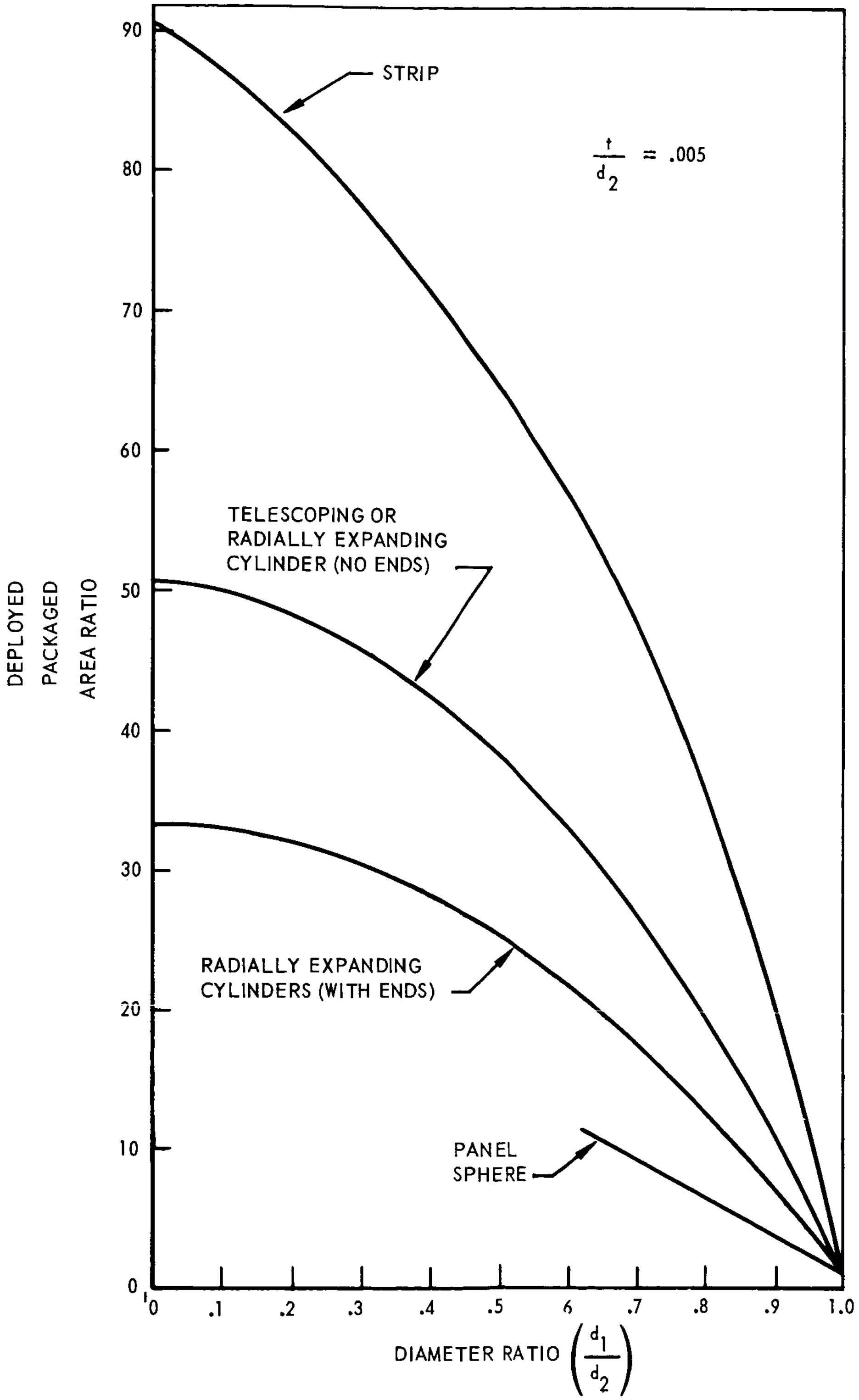


FIGURE 2-3a EXPENDABLE STRUCTURE AREA RATIO COMPARISON

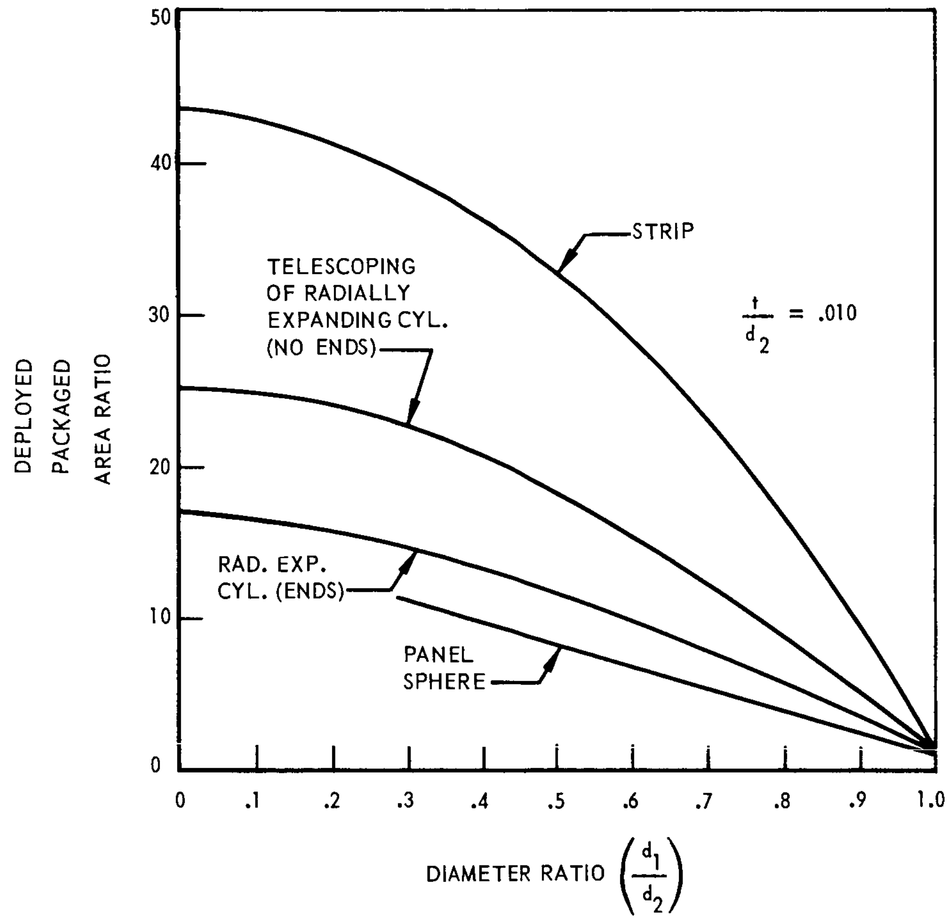


FIGURE 2-3b EXPENDABLE STRUCTURE AREA RATIO COMPARISON

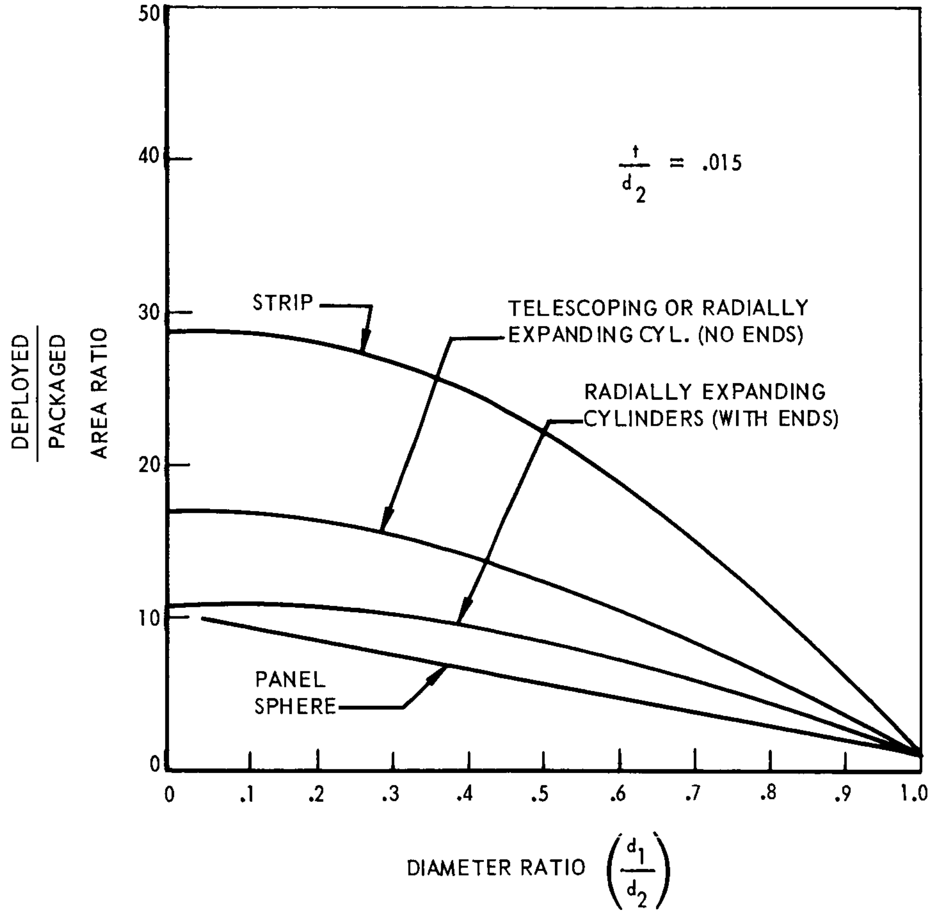


FIGURE 2-3c EXPANDABLE STRUCTURE AREA RATIO COMPARISON

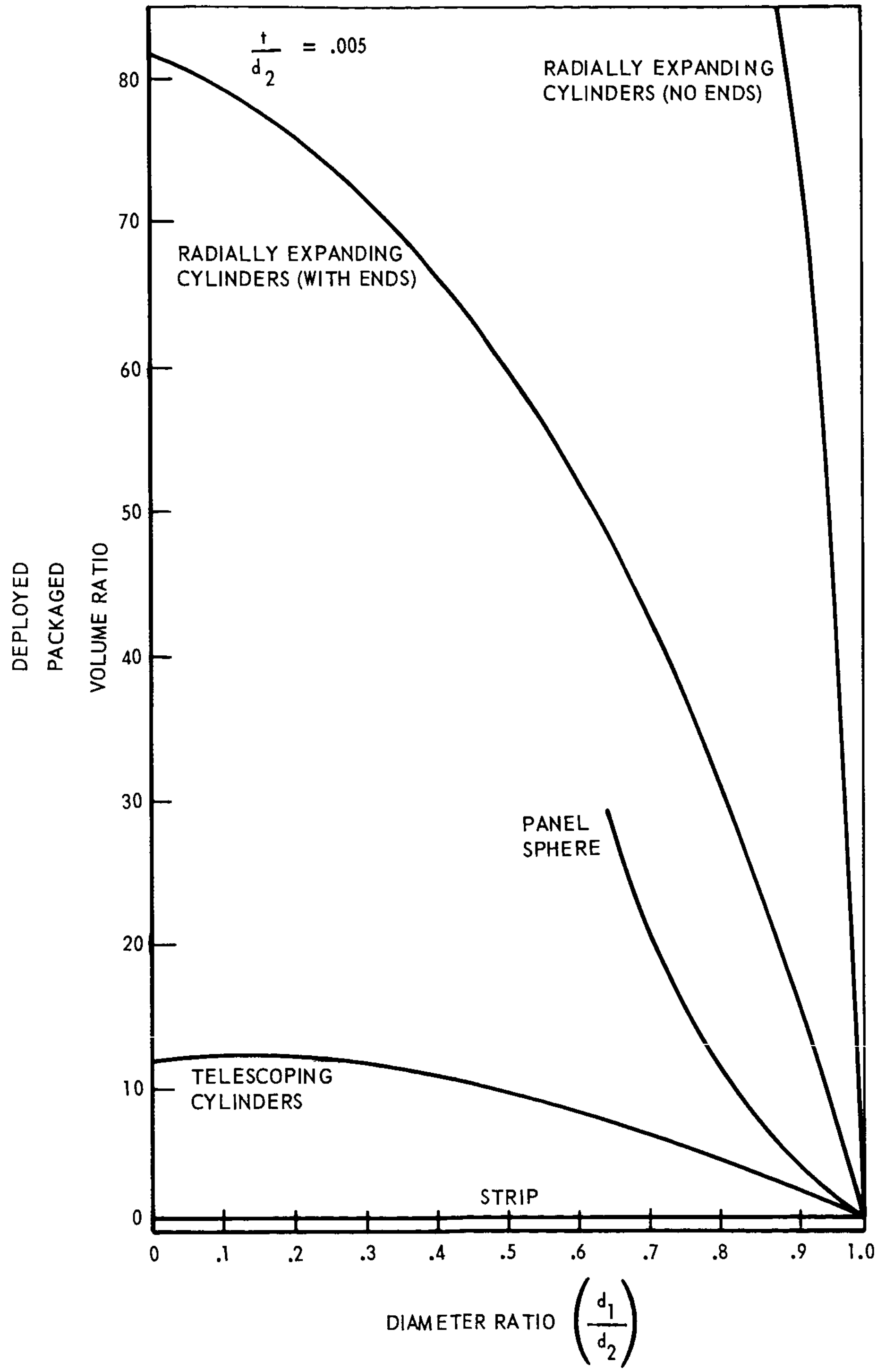


FIGURE 2-4a EXPANDABLE STRUCTURE VOLUME RATIO COMPARISON

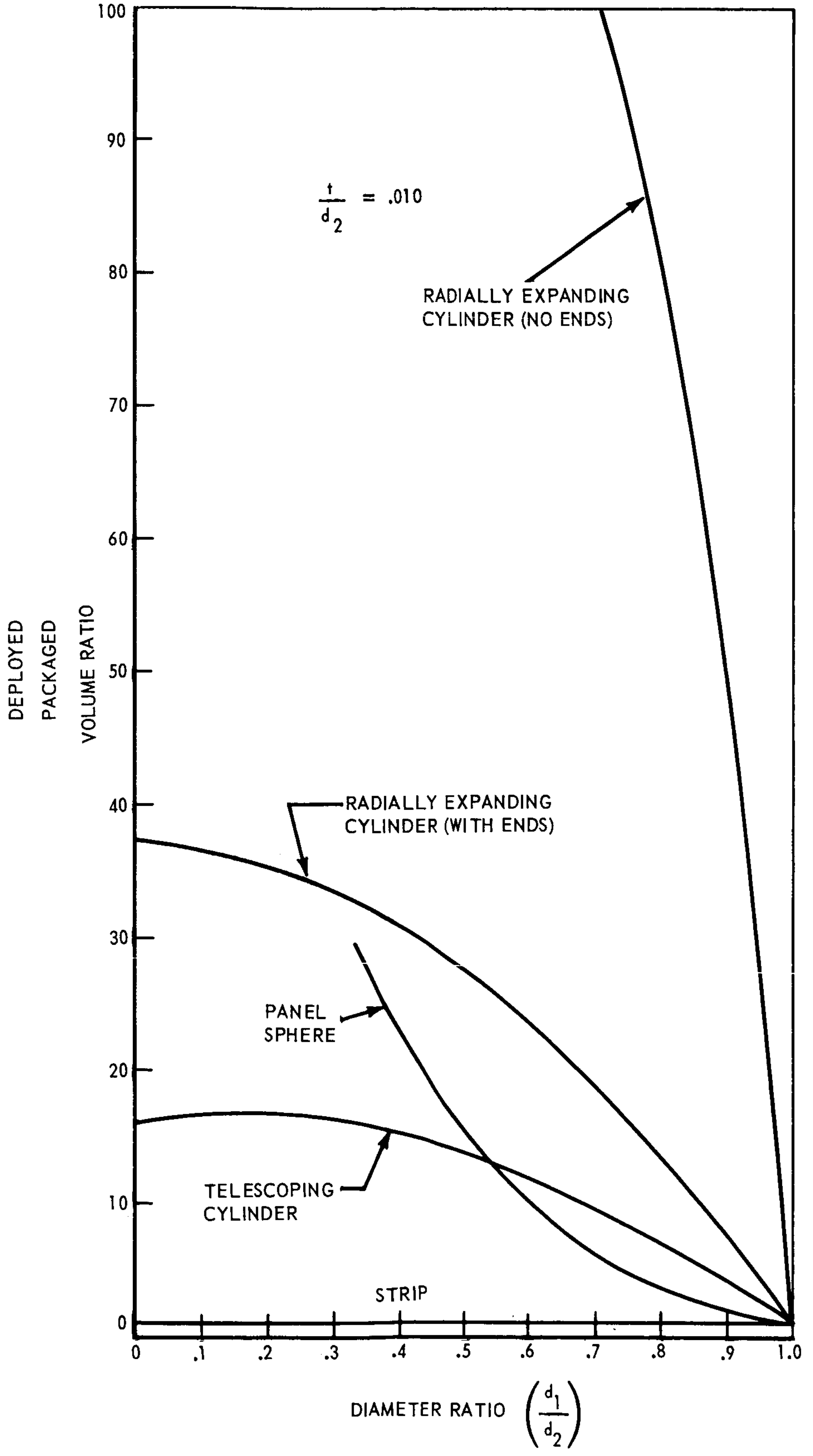


FIGURE 2-4b EXPANDABLE STRUCTURE VOLUME RATIO COMPARISON

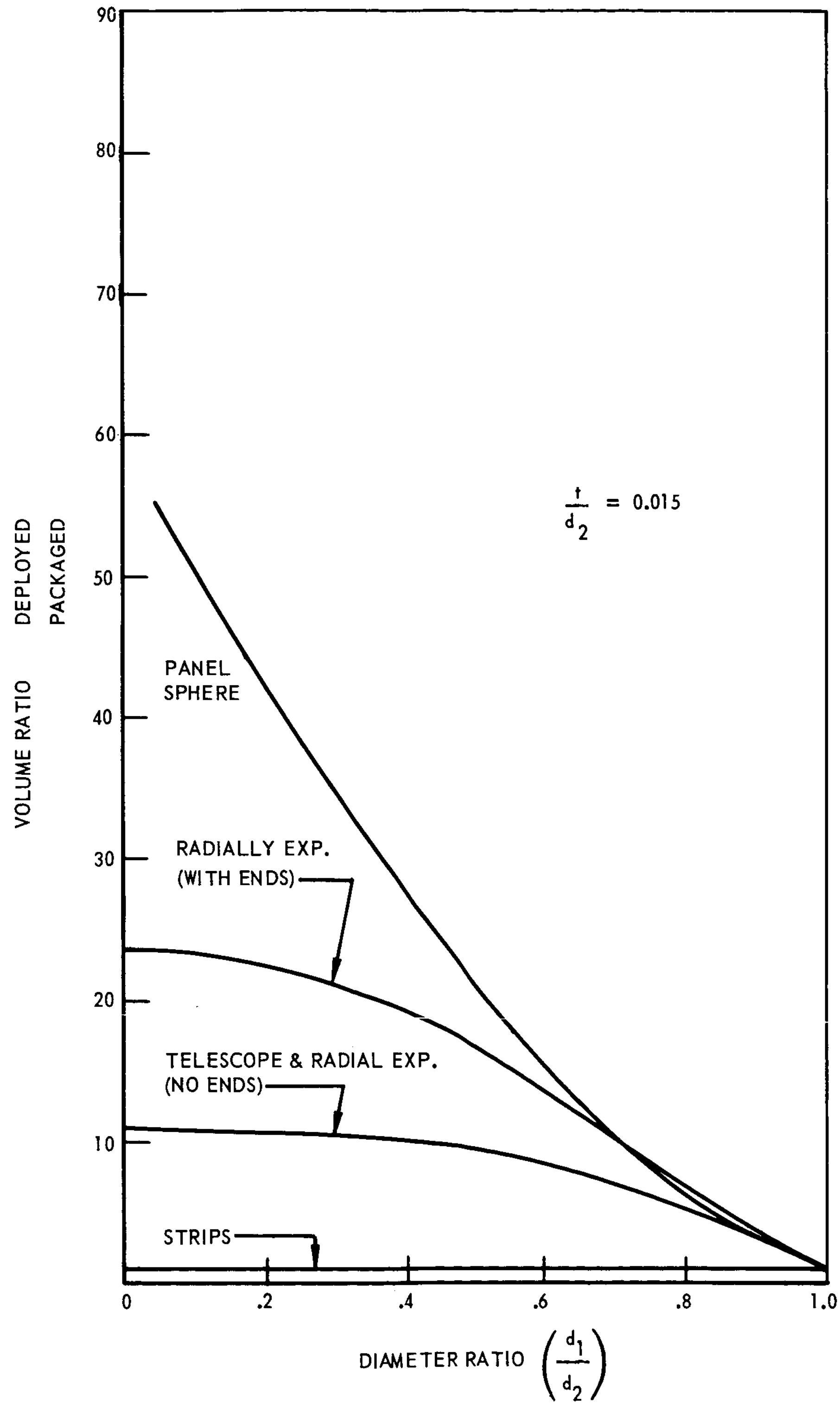


FIGURE 2-4c EXPANDABLE STRUCTURE VOLUME RATIO COMPARISON

It is concluded that the materials presently used in spacecraft structures can generally be applied here without significant development or fabrication problems. However, unique applications could require materials which are under development or where a technology is not sufficiently advanced. In this case, it would be necessary to provide for the material uncertainties with additional design considerations.

The actuation devices which may be used could apply any one or several of the energy sources and drive mechanisms presently available. The ultimate selection of a system will depend upon the size of the structure, energy requirements, volume requirements, vacuum welding possibilities, and reliability.

Locking devices could be readily incorporated with the actuation device or may be independent of it. The selection of the manner of locking the structure will depend upon the structural system and whether there are refolding requirements. However, locking devices to obtain rigidity of the structure are available and can be used with the system.

2.5 CONCLUSIONS

The VG structure has a potential of being applied in a large number of different systems. The aspect of wide application comes from the fact that VG structures are capable of deploying into many different shapes. The rigidized frameworks formed when the structure is deployed, either partially or completely, can provide cylindrical or spherical geometries, as well as various dome-type shapes. The VG structure can be integrated with other structural systems so that almost any shape can be achieved.

The frame type VG structure is capable of developing into a rigid structural framework. This framework can be used for any number of different applications; e.g., providing a basic structural skeleton or booms for various lifting systems and antennae.

The VG structure can be readily integrated with other concepts to provide a more versatile system. This can be accomplished by integrating panels or panel structures into the framework. Furthermore, pressure sealing can be accomplished by providing seals at all joints or it is possible to utilize an encapsulating bag over the network and thereby provide the sealing capacity.

The study of materials, actuation devices and locking devices shows that the present state-of-the-art is sufficient to provide the design and development of actual components for structural systems of the VG design.

SECTION III

GENERAL CONSIDERATIONS

3.1 INTRODUCTION

External loads and environmental considerations are discussed in this section, while geometric and deployment considerations are given in succeeding sections. In conventional design, the applied loads usually govern the selection and sizing of a component. In spacecraft, knowledge of the external loads is not sufficient because its design must consider the effects and consequences of space phenomena. This section will discuss, generally, some of the design considerations for VG structures.

Packaging of the VG system was also investigated by applying topological principles. The result of this investigation is reported in the latter parts of this section.

3.2 LOADING CONDITIONS

The VG structure, when launched, must be able to sustain loads from three distinct flight regimes. The first is the initial launch phase. Here, the structure will encounter loads due to atmospheric conditions and attitude of the vehicle. The second regime is space; here the structure is deployed and confronted with hostile enviornment where it may be bombarded by micrometeoroids, high-energy corpuscular radiation, and encounter extreme temperatures. The third regime is that of reentry into the Earth environment or entry into a distant planet. Heat caused by the drag forces of an atmosphere and impact loads are some of the major problems in the third flight regime.

3.2.1. LAUNCH. During this regime, the compressed VG structural package must sustain the following loads:

a. inertia

b. aerodynamic

c. thermal

d. internal pressure

e. vibration

The extent of the loading will depend upon the VG structure package and its location in the payload region. These considerations require a particular design for a complete evaluation.

3.2.2 SPACE MISSIONS. The structure, in the space environment, will be subject to loading conditions which are a function of its use and where it is in space. For example, that structure which is used as a part of a space station will be subjected to applied loads associated with docking, simulated gravitational loads, etc. However, the primary design consideration is not the loading condition but the environmental effects.

In the case of a lunar station, where nominal gravitational forces are present, their effects must be added to the other environmental conditions to determine design requirements. It is possible to classify these considerations as follows:

(1) Shielding against high-energy corpuscular radiations.

(2) Vacuum welding and/or sublimation of metals.

(3) Effects of meteoritic debris.

(4) Effects of solar radiation on the structure.

(5) Simulated gravitational force field.

The last 3 considerations are discussed in more detail in succeeding paragraphs.

3.2.2.1 Micrometeoroids. This area has the greatest amount of uncertainty associated with it. Because of possibly severe effects, it has been the subject of a number of investigations which attempt to establish the micrometeoroid environment and the effects of the hypervelocity impacts on various protection materials. This subject has been extensively evaluated in References 5 through 10 and is not considered here.

3.2.2.2 Solar Radiation. Thermal control of the space or lunar structure (Ref. 11) is a problem of great importance in the design of the structure. While the space environment generally provides a situation where the mechanical loading conditions are small, the thermal loads resulting from temperature differences, or gradients can cause loading and distortion of components. Furthermore, the thermal load can result in cycling of the structure or its components and cause fatigue failures; or it may increase the aging properties or modify the creep characteristics of the metal. The increased temperatures coupled with the vacuum environment, can increase evaporation or sublimation of certain materials. These considerations must be evaluated for any space structural system.

3.2.2.3 Simulated Gravitational Field. An artificial gravitation field, which may be provided to obtain a more comfortable environment for a manned station, will impose special design considerations on the structure. The centrifugal forces will vary from the center of rotation and have to be accounted for.

3.2.3 ATMOSPHERIC ENTRY. This design condition occurs only when the vehicle or structure is entering an atmosphere from space. If this atmosphere is Earth's, heating by the drag forces will occur. The implications of entry, insofar as the VG structures are concerned, largely depend upon the shape, size, attitude angle, etc., of the re-entry package. These are peculiar to a particular mission and must be evaluated individually.

3.3 TOPOLOGY INVESTIGATION

The conceptual investigations reported briefly in the previous sections have shown that virtually a limitless number of geometric configurations can be achieved with the variable geometry structures concept. These are attainable by varying the arch geometry, the base ring size and shape, the method of arch interlacing, to say nothing of the increased geometric scope afforded by inclusion of the panel and integrated panel-frame combinations. It is recognized that the final use of a VG structure in a space system will ultimately depend upon its capability of being packaged into the spacecraft or launch vehicle, as well as on other factors such as efficiency and expanded volume.

It appeared during this study that a systematic approach to the packaging problem was warranted (Ref. 12). One approach of developing the optimum package was to utilize the principles of topology.

3.3.1 COMBINATORIAL TOPOLOGY APPLIED TO VARIABLE GEOMETRY.

The methods of combinatoral topology (Ref. 12) suggest themselves for developing rational procedures for the packaging of configurations. (Webster defines topology as "The doctrine of those properties of a figure unaffected by any deformation without tearing or joining.") The simplicial approximation theorem appears applicable to this problem. This theorem provides a prescription (although not necessarily a unique one) by which one configuration can be mapped onto another.

This is done in such a way that discrete pieces of the given configuration (deployed VG structure) are mapped on the discrete pieces of the image configuration (package VG structure). The mapping amounts to the folding of the one configuration onto the other.

The theorem is stated in terms of a continuous function that maps the one configuration on to the other in an arbitrary manner, the only restriction being continuity. If a triangulation is given to each configuration (i.e., each configuration is considered to be made up of a collection of triangles), the theorem furnishes a piece-wise linear map that maps triangles of one configuration on to triangles, sides, or vertices of the other configuration. This linear map, in a sense, approximates the given function in that they both carry vertices of the triangulation of the deployed configuration into the same triangle of the folded configuration. In order to carry out the linear mapping, it is required to sub-divide the deployed configuration so that the resulting triangles are small enough to fit neatly on to the triangles of the packaged configuration. The first subdivision is obtained by drawing in all medians of all triangles and considering all triangles so formed. The nth subdivision is then obtained by repeated application of this process. The degree of subdivision is dependent upon the given continuous function and the nature of the triangulation of the packaged configuration. In application, the subdivided triangulation of the deployed configuration is realized by a hinge for each segment common to two triangles. The linear map then tells how the deployed configuration can be folded into the packaged configuration along these hinges so that each triangle of the one configuration folds onto a triangle of the other configuration.

In selecting the continuous function and the triangulation of the packaged configuration, it is well to consider the degree of subdivision of the deployed configuration necessary to obtain a linear map. It is of course desirable to require only a minimal subdivision since the necessary hinging is related to the degree of subdivision.

As an example, consider the case where the deployed configuration is the surface of a tetrahedron and the packaged configuration is a single triangle. If we take the continuous function to provide the projection of three faces onto the fourth, the simplicial approximation theorem will require that the linear map leave the base triangle fixed, map one of the other three faces onto the base, and collapse the remaining two faces onto the edges common with the base. In this case no further subdivision is required. If, however, one should select, for the packaged configuration, a triangulation consisting of two triangles, then the deployed configuration would have to undergo one stage of subdivision. The resulting linear map would degenerate all but four of the triangles of the subdivided triangulation by mapping them onto edges or vertices of the packaged configuration. The remaining four would naturally be mapped onto the two triangles of the triangulated packaged configuration. This degeneration would require hinging in addition to that derived from the subdivision. For this reason such a scheme would be undesirable.

The methods of topology can provide a means of prescribing how the deployed VG structure can be packaged. However, it is not presently known whether this prescription will result in a package which is physically capable of achievement when constraints due to hinging are considered. For this reason, it is not certain that the principles of topology can be of assistance in prescribing folding methods. The investigation to date has only considered the generalities of the theorems; their applicability to a physical packaging problem has not been explored in any depth.

The prospect of having a systematic and rational method of folding and locating elements of a package to fit within a prescribed volume is an alluring one. If such a methodology could be developed it would substantially reduce the trial and error techniques which have to be employed at this time.

SECTION IV

FRAME STRUCTURES

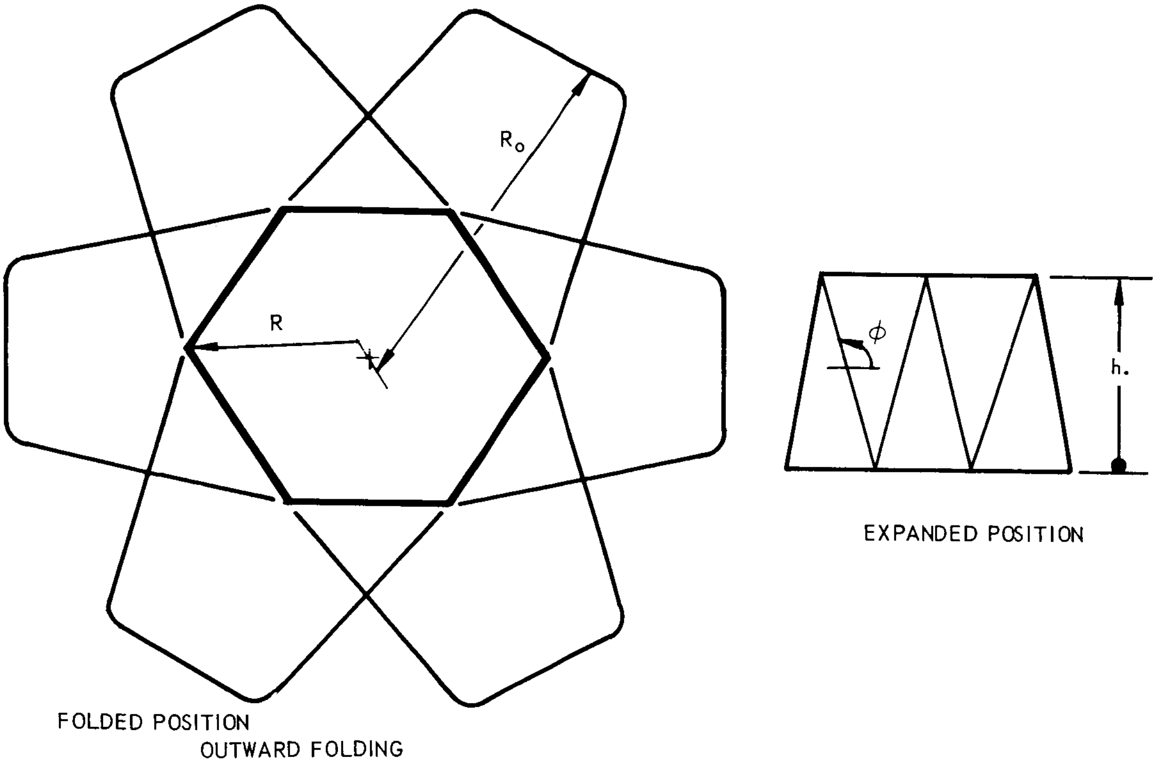
4.1 INTRODUCTION

The deployed-frame structure provides a rigid structural network which can be formed into a vast variety of configurations. The resulting structure can be used for resisting imposed loads and/or providing a skeleton whereupon panels or other enclosures can be attached.

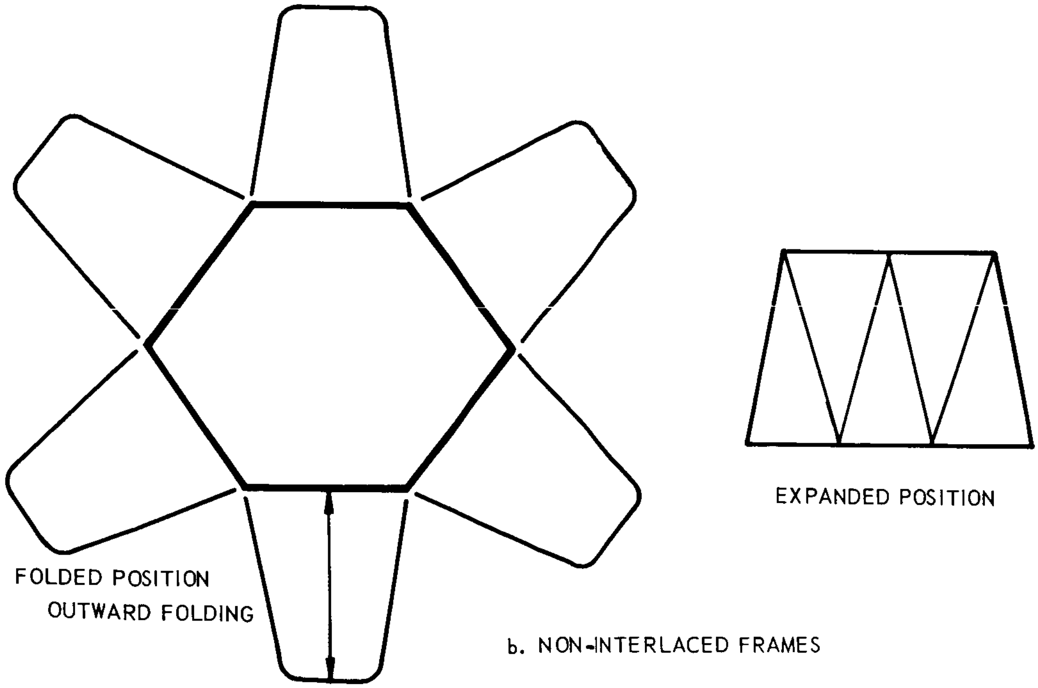
The basic element of this configuration is an arch which is hinged to a fixed polygonal ring. (Fig. 4-1). By using a number of these arches and rotating them about the fixed ring, this assembly can develop from a flat, compressed condition to an expanded shape. In some cases it may take a form approximating a sphere at intermediate stages, to one approaching a circular cylinder when completely extended.

It is possible to utilize a number of different arch configurations in this system. The possibilities considered here are the triangle, semi-circle, and trapezoid. Other shapes like the parabola and ellipse or more highly optimized geometries for specialized applications may also be used.

The method considered for moving the arches into position from



a. INTERLACED FRAME



b. NON-INTERLACED FRAMES

FIGURE 4-1 VARIABLE GEOMETRY FRAME LACING

the compressed state is the use of actuation devices attached to the framework at key locations. This is covered more extensively in Section 7.

In the fully extended position, devices may be used to lock the chord members together and the framework can then be treated as a classical two-force member framework. This configuration has the advantage that the applied loads are developed as axial loads in the structure and maximum utilization of the frame material is achieved.

One of the major advantages of this system is its ability to form into a greatly expanded, yet rigid, structure; another is its ready adaptation to modular construction. This permits a wide variety of structures to be formed for almost any conceivable usage.

The structures under consideration in this section are single and two-stage. The use of multiple stages involves only a nominal extension of these principles.

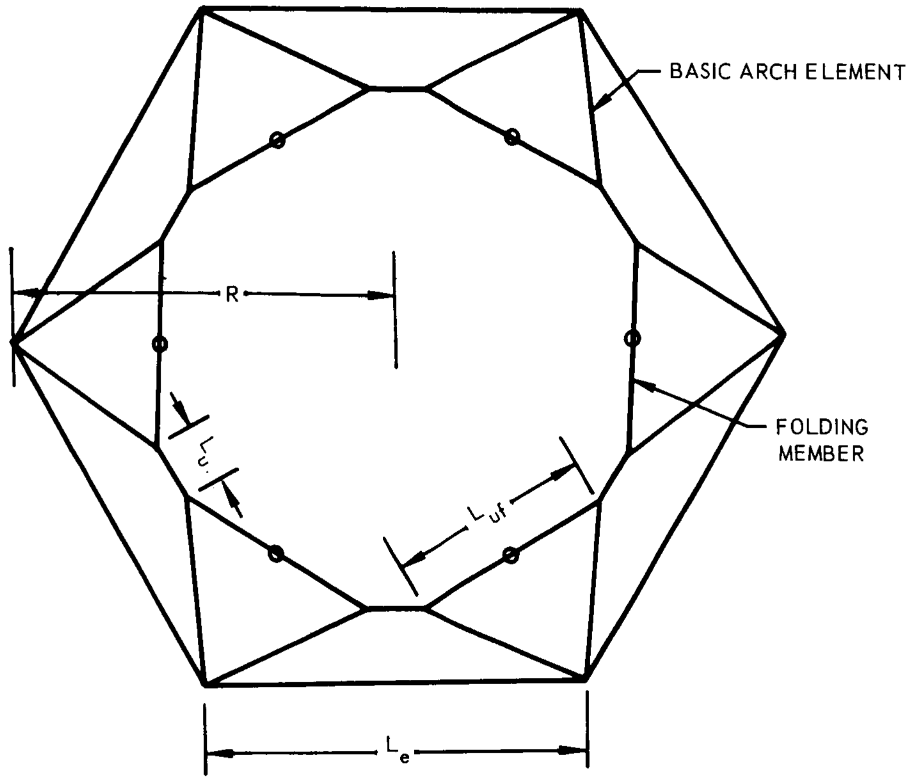
4.2 SINGLE STAGE SYSTEMS

The basic system which can be isolated from the complex of configurations will be referred to as the single stage. Therefore, the initial discussions will establish its basic characteristics.

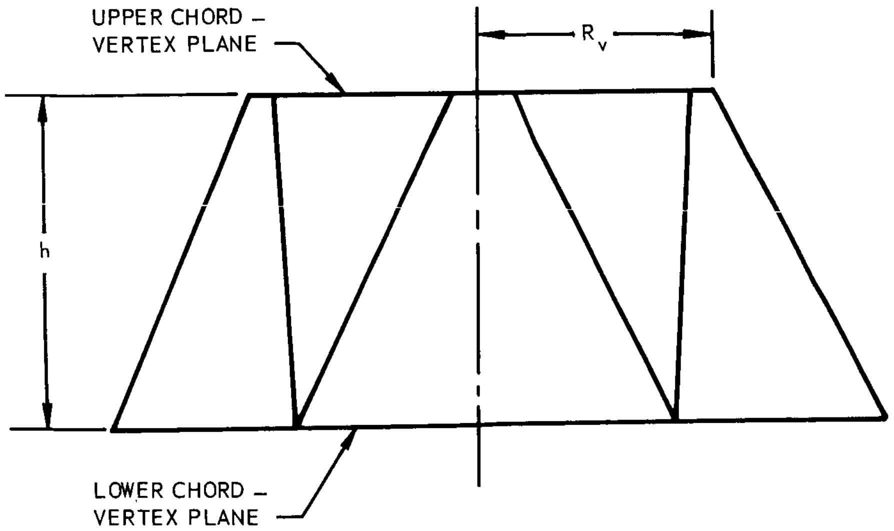
The frame structures can conveniently be categorized into interlaced and non-interlaced configurations. Examples of these are shown in Figure 4-1. Further variation can be achieved by the manner in which the arches fold or rotate about the fixed base ring to the flat state. That is, they may fold inward or outward. An example of an inward fold is shown in Figure 4-2.

The arches making up the frame structure can be varied into a number of geometrical configurations. It is obvious that when one combines the manner of interlacing, the manner of folding, and the variations in the arch geometry a vast number of combinations is possible. This study placed major emphasis on the trapezoidal arch considering both inward and outward folding techniques. While it is not all encompassing, considering all of the variations possible, it does provide a good foundation whereby the basic modes, behavior, and principles of deployment can be evaluated.

The interlacing of adjacent arches forming the VG structure was felt to be an important area of investigation. For the non-interlaced arch it was found that the configuration resulted in a less stable structural array than did the interlaced design. Furthermore, the design is not as readily adaptable to actuation techniques as is the interlaced case. The interlaced geometry provides a more stable configuration, and the actuation techniques are greatly simplified. This is discussed in Section 7. The study described there emphasize the single interlaced configuration. (Single-interlace refers to the condition of only one contact point - exclusive of the hinge - between



PLAN VIEW – DEPLOYED POSITION



ELEVATION – DEPLOYED POSITION

FIGURE 4–2 TRAPEZOIDAL ARCH SYSTEM ~ INWARD FOLDING, NON-INTERLACED

adjacent arches.) It is possible to obtain a greater degree of interlacing by increasing the number of sides to the polygon and the number of arches, and by varying the hinge location. Qualitatively, however, it appeared that the single degree of interlacing provides enough stability to enhance the structural characteristics and yet minimize the actuation requirements.

The arch may be a flat, planar member or it may possess curvature along its length. If the latter, the deployed structure will take the form of a paraboloid or a spheriod. This structure can also be interlaced to obtain greater stability and better actuation. However, it will not assume a flattened position when disassembled and may require more packaged volume than does the planar structure.

4.2.1 TRAPEZOIDAL ARCHES

4.2.1.1 Outward Folding Interlaced Frames. The outward folding interlaced arch system is shown schematically in Figure 4-3. The various dimensional quantities are shown in the figure. The base ring is fixed in size by selection, as are the arches. These fix the maximum radius (R_o) of the compressed structure and hence the package diameter.

Figure 4-3 shows the base ring as a hexagon. However, a design using a minimum of four sides can be made with interlacing. The

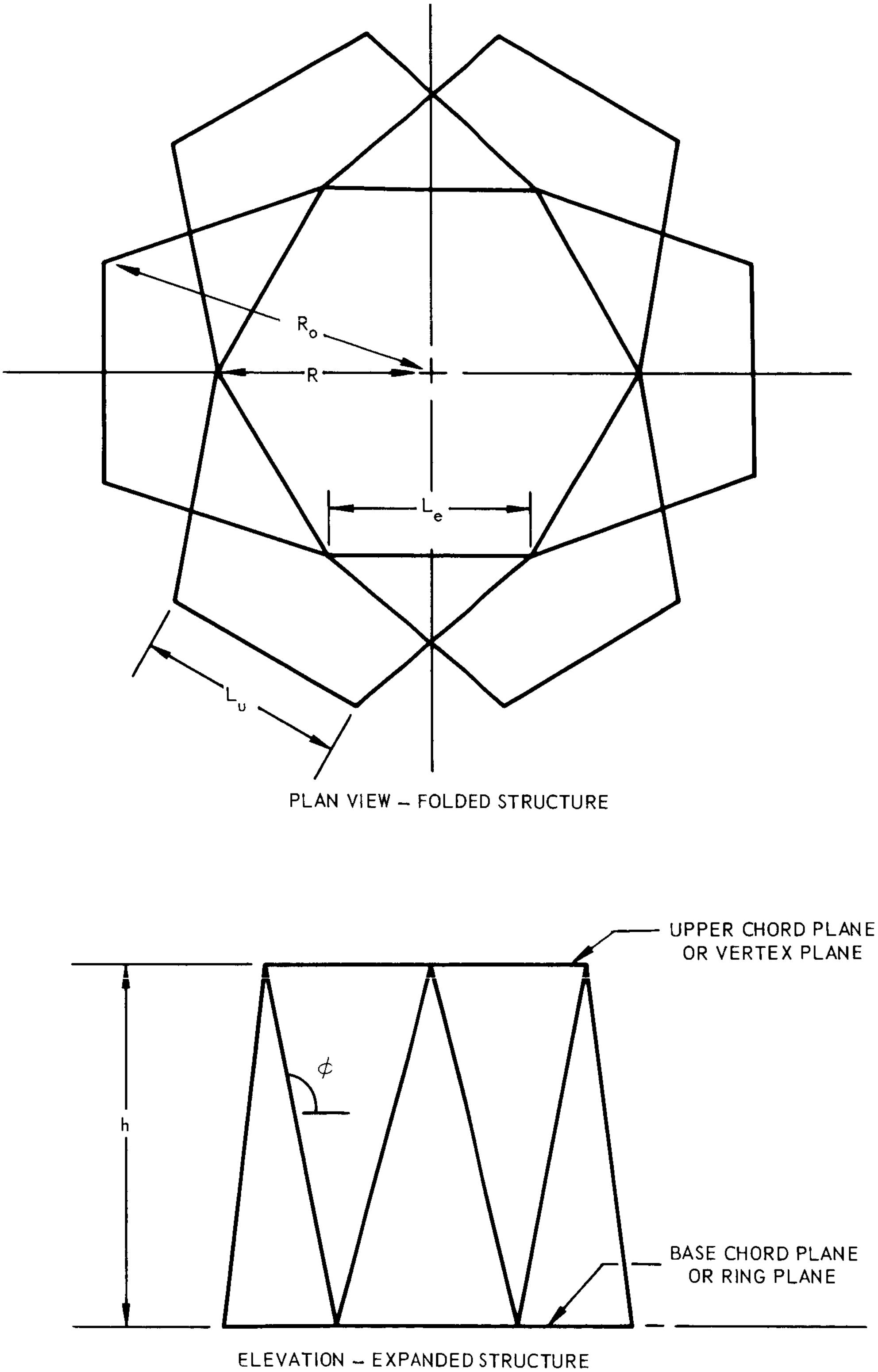


FIGURE 4–3 TRAPEZOIDAL ARCH SYSTEM –OUTWARD FOLDING INTERLACED

maximum number of sides would be dictated by considerations involving stability, number of hinges, and actuation device requirements. It appears, from a qualitative standpoint, that a six to ten-sided polygon would be most practical. The corners of the base ring polygon form the attachment locations for the arches. These are attached at alternate corners and, when placed in the final deployed configuration, form another polygon with an equal number of sides but rotated with respect to the base ring. The size of the formed polygon depends on the width of the apex of the archessince the top forms one side of the developed polygon. By way of definition, the plane in which the base ring lies is called the lower chord, or ring, plane and the plane of the developed polygon is called the upper chord, or vertex, plane.

Figure 2-1 shows a model of a deployed two-stage trapezoidal arch system. It will be noted that the resulting structure forms a triangular space structure. The relative increase in the contained volume is substantial when one considers its nominal initial volume.

4.2.1.2 Inward Folding Interlaced Frames. The inward folding structure is of particular interest because it can be compressed into a smaller volume by folding the arches inside of the base ring. One example of an inward folding, interlaced, trapezoidal arch system is given in Figure 4-4. This particular system uses trapezoidal arches which hinge at alternate corners of the polygon to provide the interaction effect.

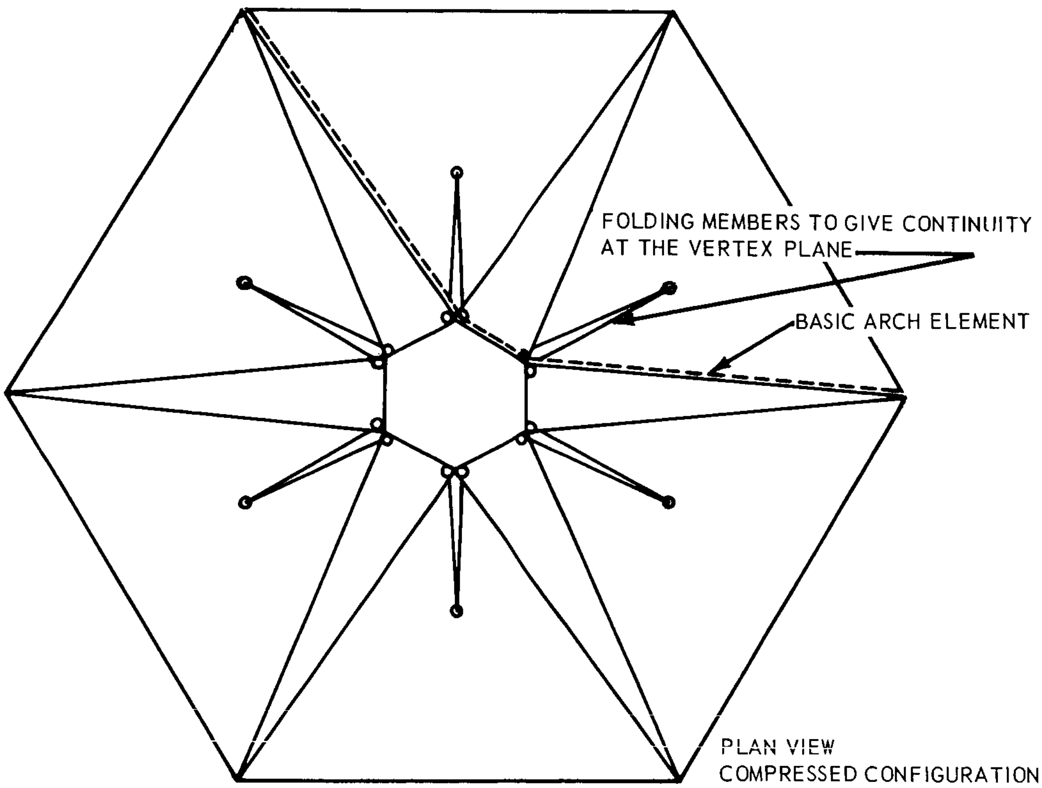


FIGURE 4-4 TRAPEZOIDAL ARCH SYSTEM — INWARD FOLDING, INTERLACED

The structure is deployed by moving the arches in an axial direction (outward from the paper); they are locked into final position with the assistance of folding members which connect the tops of the arch frames as shown in the figure. Stability of the framework is achieved in this manner.

The frame height, h, of the inward folding structure is constrained by the geometry of the folded configuration. This constraint places a maximum on the value which h may attain; the limiting case being when the arch approaches a triangle with its side member length being equal to the fixed ring radius, R, and h equal to R cos (π/N). In a practical system, it is not feasible to use triangular arches. Therefore, for this investigation an arbitrary reduction factor was employed such that the maximum usable h is assumed to be .85 R cos (π/N).

It will be noted from the figure that more members are required for this framework than for the outward folding trapezoidal arch system. The additional members, with the upper chord members, form a closed polygon in the upper chord plane when the framework is in its expanded configuration. The additional members necessarily fold at their mid-point and their length is directly determined by the desired expanded configuration. The length of the folding members controls the expanded configuration parameters and geometric relationships.

In its expanded position, the inward folding structure may be considered a classical pin-jointed truss similar to the outward folding structures. These, when fully deployed, are also stable for all external loading conditions.

4.2.1.3 Non-Interlaced Frames. It is possible to utilize frames which are not interlaced and can also fold to fill the base ring volume. If desired, the maximum arch height will be approximately the distance across the flats of the polygon. However, the resulting compressed structure is not compact in that a height outside of the base ring will occur because of stacking of the arch elements.

A typical non-interlaced trapezoidal arch system is shown in Figure 4-1b. Non-interlaced structures can fold inward or outward to form a packaged position. The non-interlaced arch system in a deployed state does not have continuity at the joints of the developed upper chord plane. This continuity is required to achieve stability and, therefore, additional devices or members are required. The geometrical relationships and folding kinematics of the non-interlaced structure are constrained in a manner similar to that of interlaced structures. The main advantage of non-interlaced structures compared with interlaced structures is that the former will package into a compact launch configuration which has approximately one-half the thickness of the launch configuration of an interlaced structure. This is the result of the elimination of overlapping layers of the frame in the folded position.

The main disadvantage of the non-interlaced trapezoidal arch systems is that separate actuation must be provided for each arch.

4.2.2 TRIANGULAR ARCH SYSTEMS. The triangular arch system uses frames which approximate a triangle and fold into a near conical structure when deployed. The location of frames by attachment to a base ring is identical to the case where a trapezoidal or semi-circular frame is used. The methods of interlacing the number of sides to the base ring are identical to those discussed in Paragraph 4.2.1

The load carrying capability of the structure is similar to that for the trapezoidal framework. The resulting framework is a structure of triangular panels.

A nested set of triangular arches is shown in Figure 4-5.

4.2.3 SEMI-CIRCULAR ARCH SYSTEMS. A typical semi-circular arch system, with nomenclature, is sketched in Figure 4-6. The arch may fold inward or outward and may be non-interlaced, singularly interlaced, or multi-interlaced. As was shown in paragraph 4.2.1.2, the radius, r, of the arch element must satisfy the relation,

$$r = .85 R$$

The figure depicts the conpressed position of an outward folding system as well as the expanded or operational configuration which is obtained by rotating the arches inwardly. The degree of interlace employed in

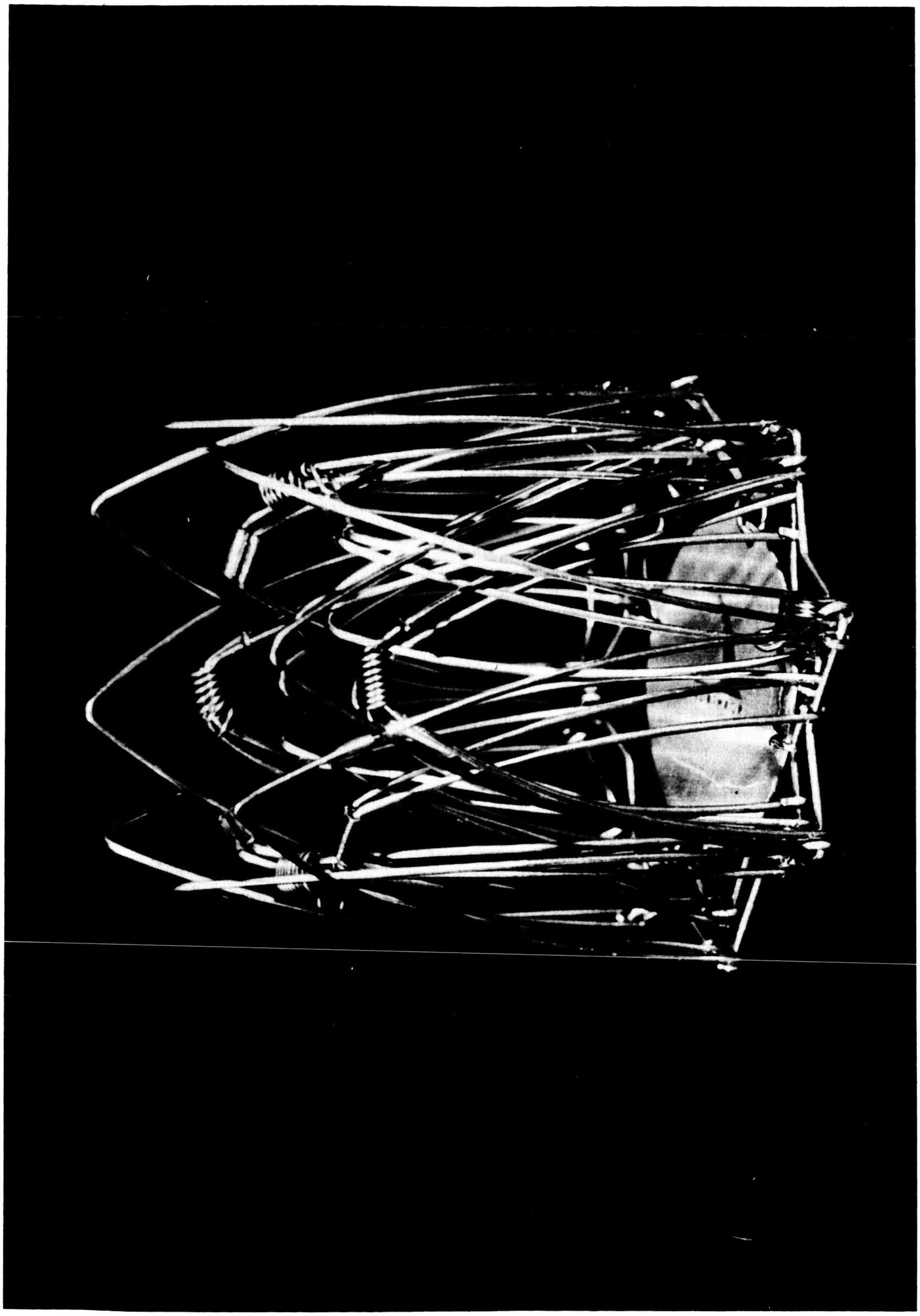


FIGURE 4-5 FOLDED TRIANGULAR ARCH FRAME STRUCTURE

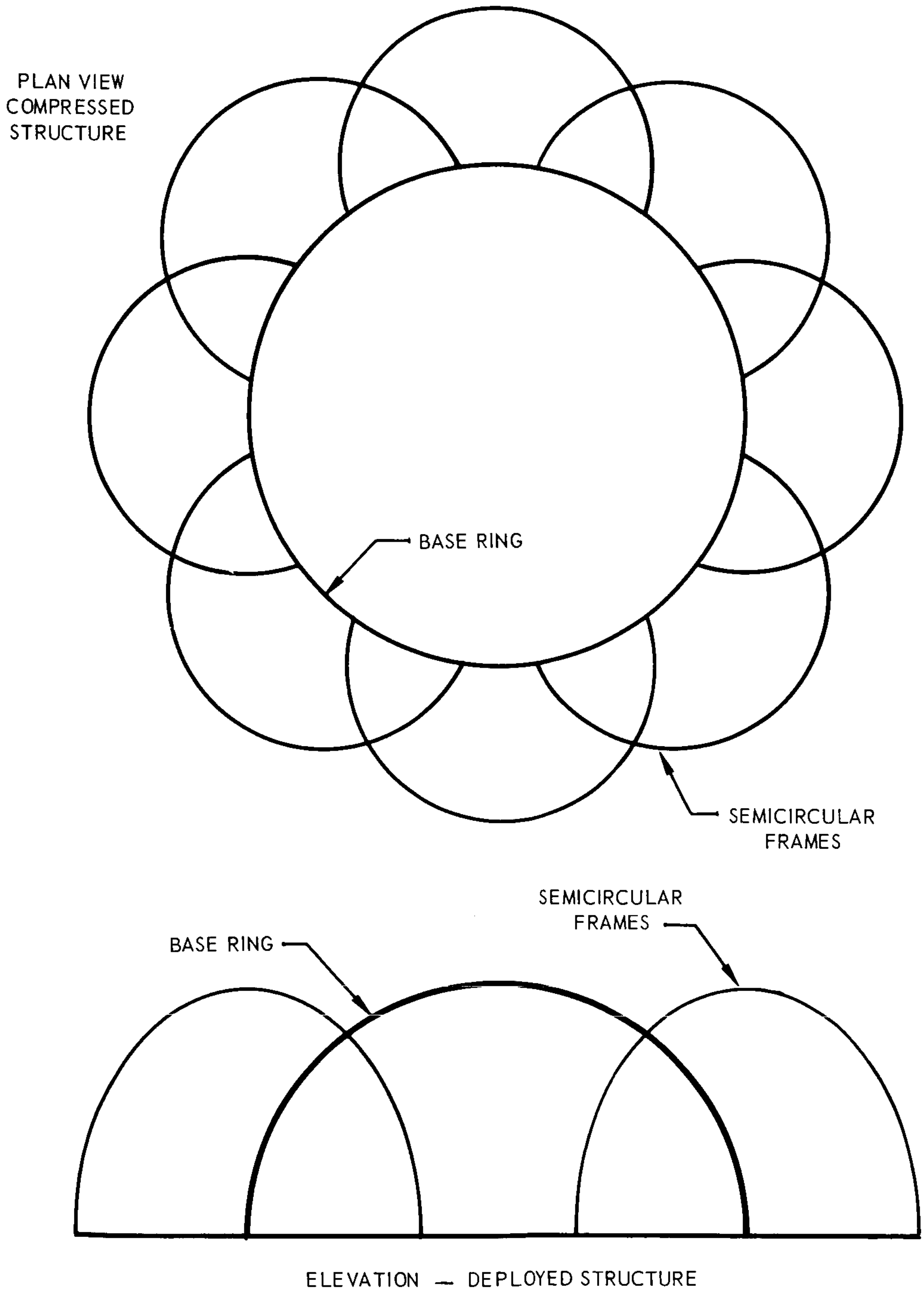


FIGURE 4-6 TYPICAL SEMICIRCULAR ARCH SYSTEM

a semi-circular arch system is basically a function of the purpose for which the system is designed, and the degree of redundancy required for operational life expectancy.

The outward folding semi-circular arch system is of special interest because of the near spherical volume enclosed when the configuration is deployed. The spherical geometry provides a minimum surface area to enclosed volume. This feature is important because the weight of a space structure is a direct function of the weight per unit surface area that is required for environmental protection. The over-all weight efficiency may be improved by minimizing the ratio of surface area to enclosed volume. The detailed examination of semi-circular arch systems reveals that the single-stage system itself is not a true hemispherical shape. The hemispherical shape is more closely approached as the number of arches increases and the size of the flat panels between the arches decreases.

Loads transmitted through semi-circular arches introduce bending moments in the arch elements. The bending of an element is an inefficient method of carrying load when compared to the axial load capability of a truss. Consequently, any system with curved elements will have a decided weight disadvantage. In order for a semi-circular arch system to be stable while subjected to load, the arches must be locked in position in the final configuration. This may be done by a combined actuation-locking system. The stability of the framework under most loading conditions is an estimation, as a rigorous analytical technique for semi-circular arch systems is unresolved at the present time.

Semi-circular arch systems appear to be the least practical of all expandable arch systems; this is mainly due to the weight disadvantage, actuation and locking complexity, and enclosure difficulty.

4.2.4 SURFACE AREA AND VOLUME RELATIONSHIPS

Three characteristics of importance in the selection and design of an expandable structure are volume, surface area, and height, for various states of deployment. Relationships expressing these characteristics are taken from Reference 14 using the assumption that the shape of the configuration at any stage of deployment is the frustrum of a right circular cone. Actually, the overlapping, voids, and pockets formed by the arches will result in an irregular surface which varies according to the deployment state.

The applicable equations of Reference 14 were made non-dimensional by the introduction of appropriate multipliers and are listed below and plotted in Figures 4-7 and 4-8:

Height ratio: $$h/l = \sin \phi \tag{4.1}$$

Area ratio: $$A/R_o^2 = \pi \left[1 + (h/R_o)^2\right]^{\frac{1}{2}} \left[1 + R_u/R_o\right] \tag{4.2}$$

Volume ratio: $$V/R_o^3 = (\pi/3)(h/R_o)\left[(R_u/R_o)^2 + R_u/R_o + 1\right] \tag{4.3}$$

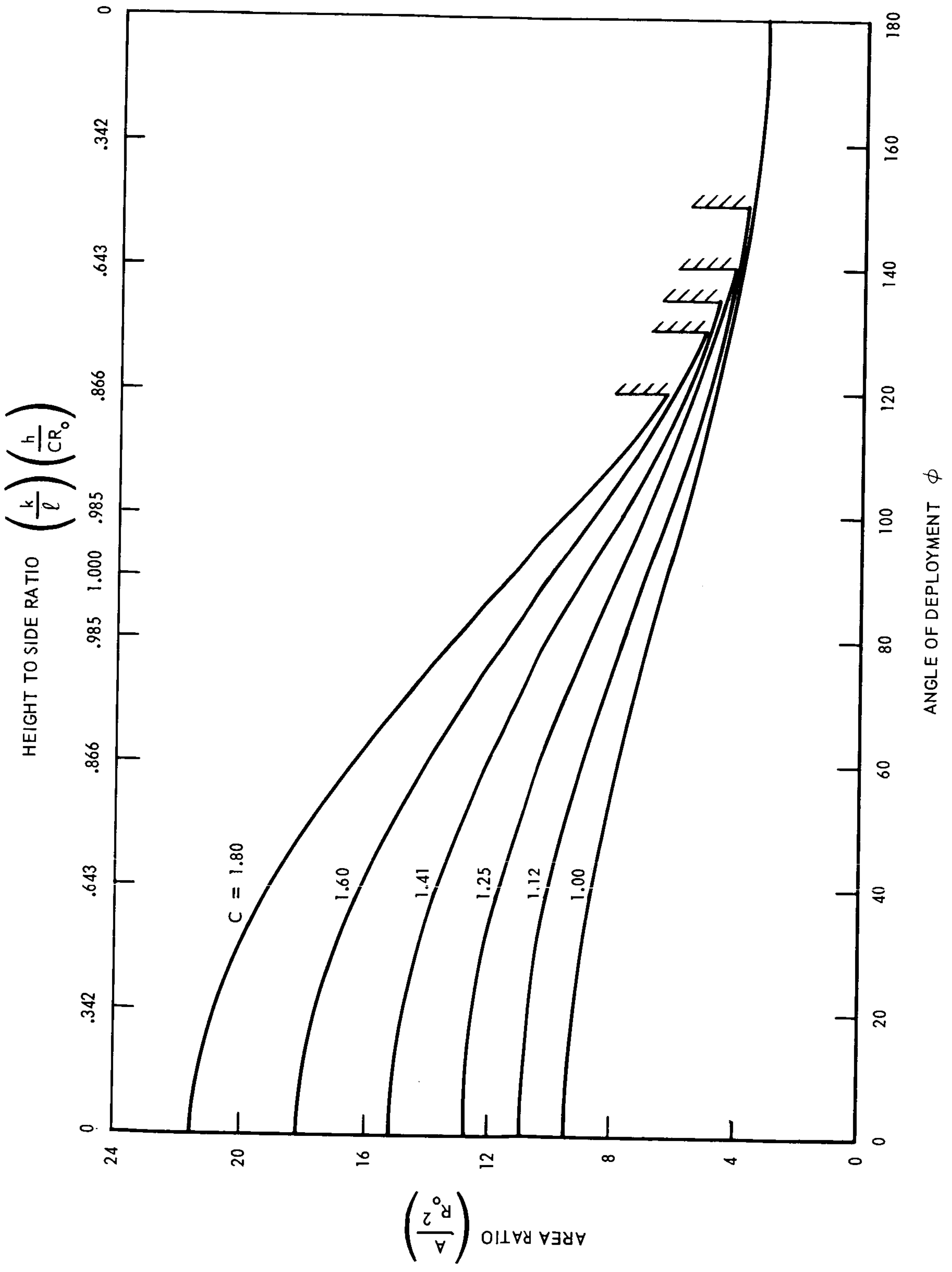


FIGURE 4-7 AREA RATIO VS ANGLE OF DEPLOYMENT

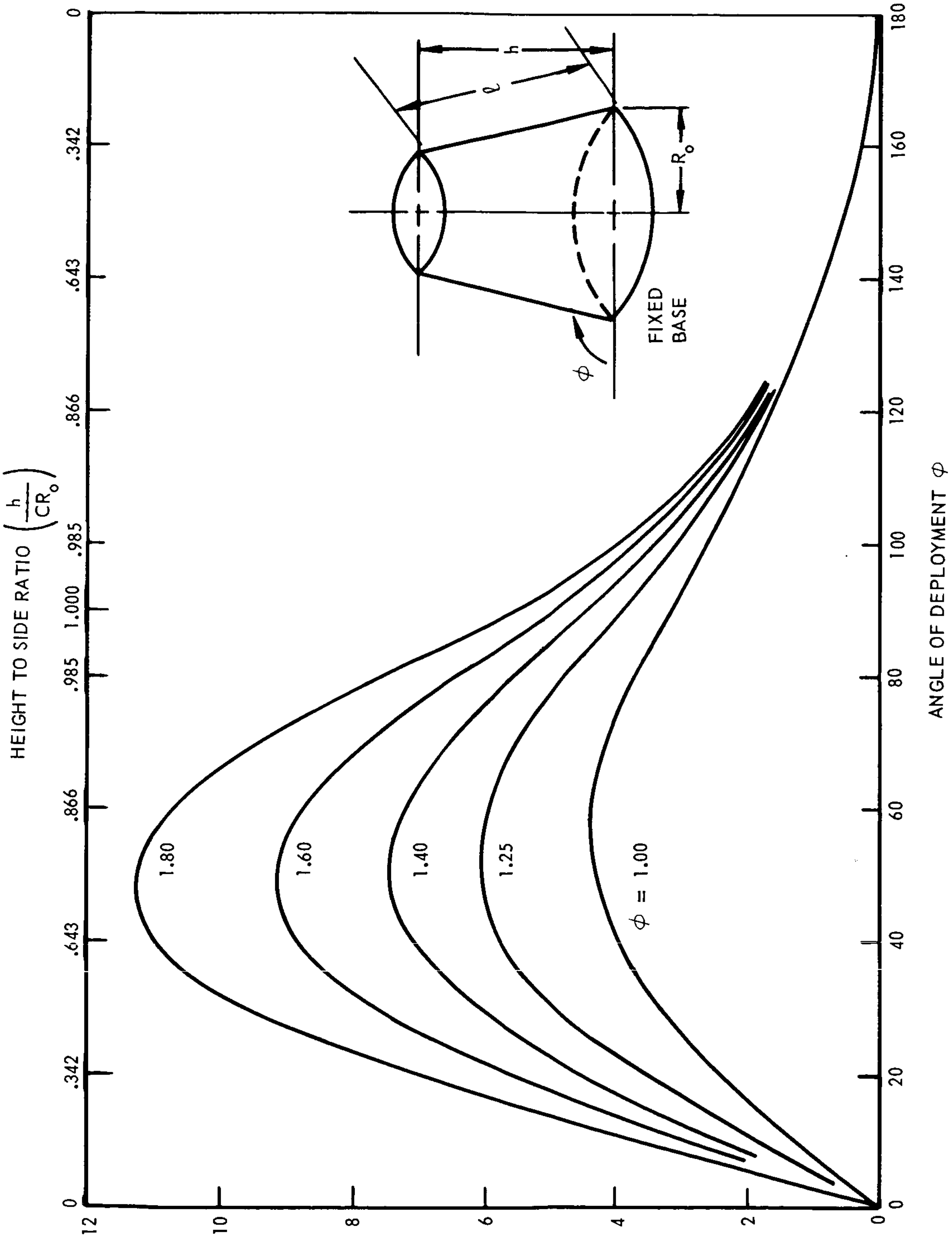


FIGURE 4-8 VOLUME RATIO VS ANGLE OF DEPLOYMENT

Where: h = height of cone

l = slant height = arch height

R_o = base ring radius

R_u = vertex ring radius

V = volume

A = area

4.3 MULTIPLE STAGE SYSTEMS

Multiple stage variable geometry structures are formed by the integration of single-stage structures into one system. A two-stage structure may be formed by attaching two single-stage structures at the vertex plane, as shown in Figure 2-1 or by two single-stage structures having the same base chord plane ring. Similarly, additional single-stage structures can be added to obtain as many stages as practical or desired.

The multiple stage feature of the variable geometry structures also makes it adaptable to modular type construction. Variations in the structure can be readily accommodated by using different arch configurations or by varying the extent of deployment. This feature will permit variations in volume, surface area or interior shape as might be imposed by a system.

The extent of variation permitted in variable geometry structures can be readily seen in the following figures. Figure 4-9 shows an outward folding interlaced triangular arch system in a modular form.

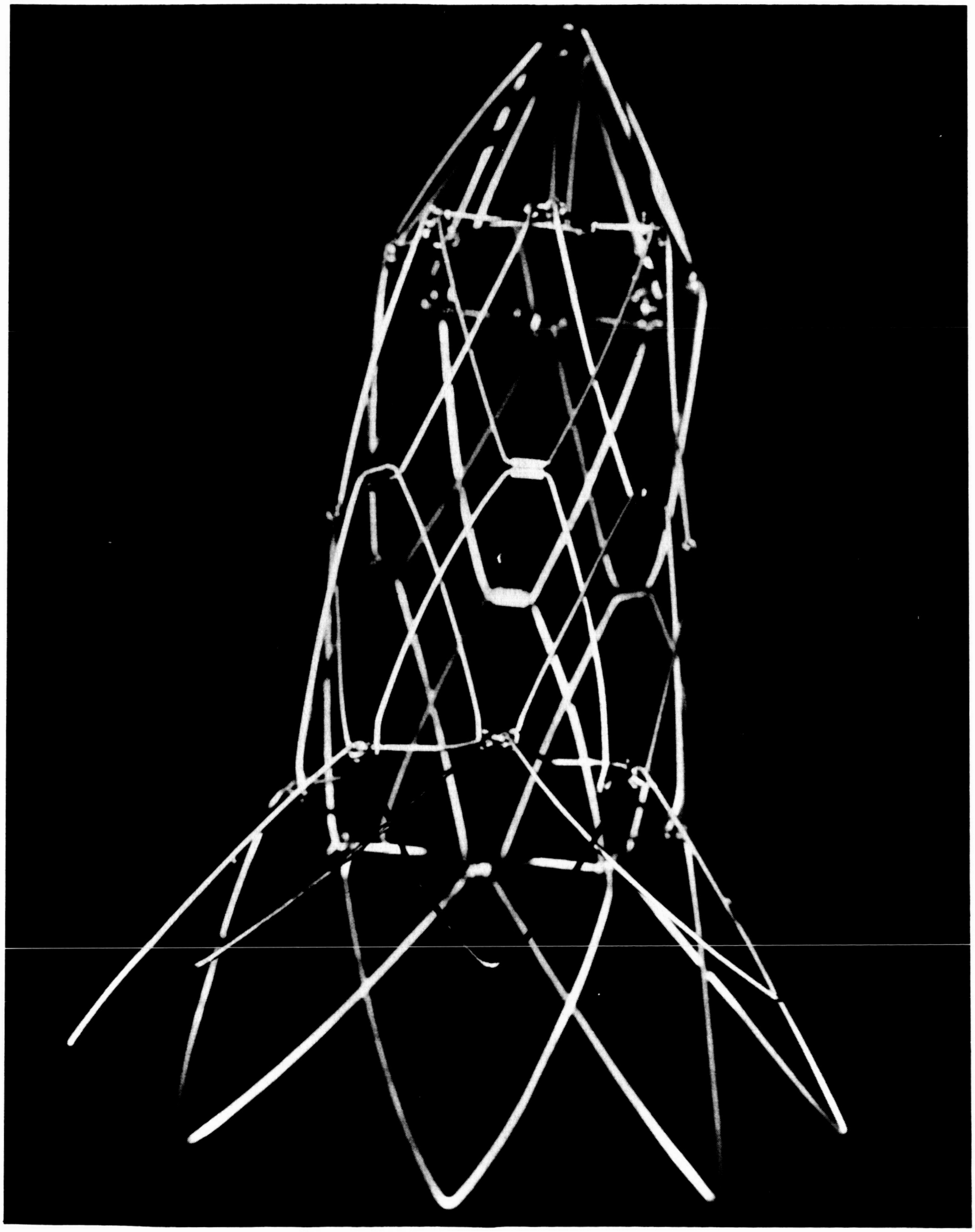


FIGURE 4–9 TRIANGULAR ARCH, MULTIPLE STAGE SYSTEM

Figure 4-10 shows the semi-circular arches dispersed about a circular base ring and interlaced, forming a "dumbell" type spherical structure.

Figure 4-11 shows the inward folding trapezoidal arch system forming a torus. This is accomplished by varying the frame height of the single-stage structure element such that the vertex plane forms an angle with the base ring.

4.4 KINEMATIC STABILITY

The framework of the deployed VG arch must be capable of forming a stable structural system. This system may be required to resist applied loads in addition to its own weight or mass. The evaluation discussed here is applicable to the frame structure forms which give a structural system consisting of two force members only: that is, bending is not present.

4.4.1 SINGLE STAGE FRAMEWORKS

The framework must possess a proper number of members, properly disposed, to ensure the stability of the framework. If the framework is unstable, it will permit rotation at the joints and become kinematically unstable, which will result in collapse. The situation here is identical with the case where a pin-jointed, two-dimensional rectangular framework is without a diagonal. The application of a load

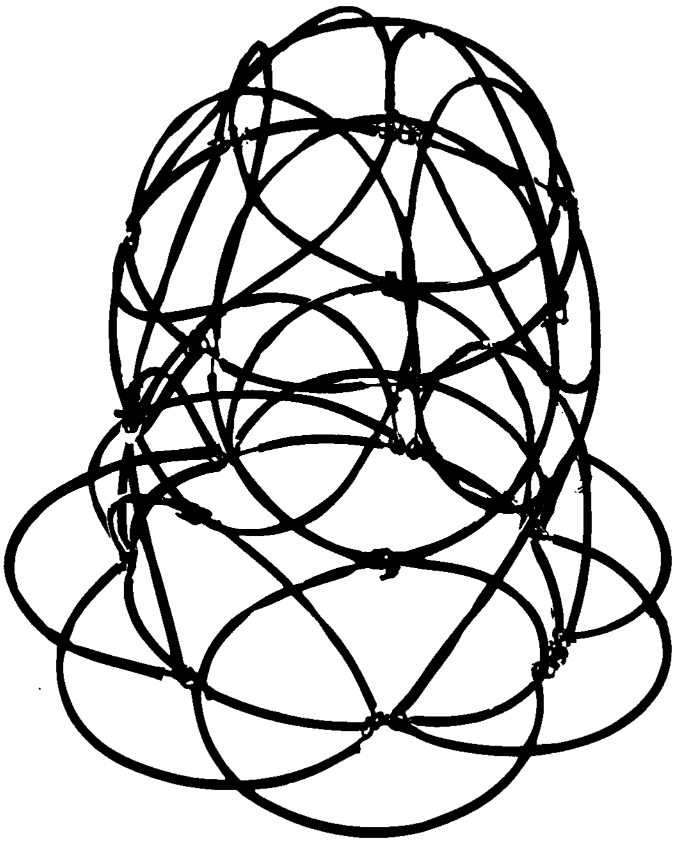
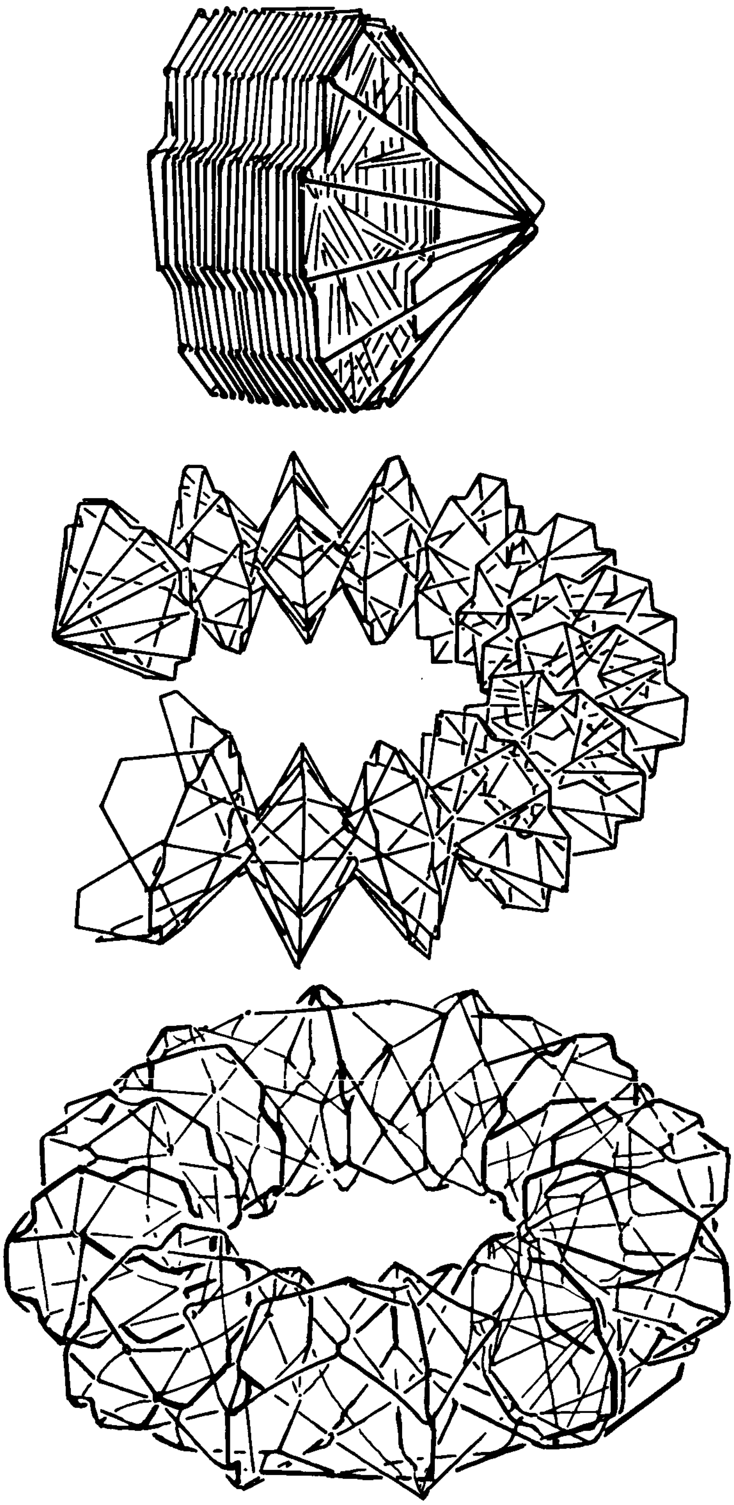


FIGURE 4–10 SEMI-CIRCULAR ARCH, MULTIPLE-STAGE SYSTEM



(A)

(B)

(C)

FIGURE 4-11 TORUS FORMED BY MULTIPLE-STAGE VARIABLE-GEOMETRY STRUCTURE will cause instability and collapse.

One method of determining the stability of a framework is the use of tension coefficients. The tension coefficient is defined as the force in a given member divided by the length of that member. This results in an expression for the force in a member which consists of the tension coefficient and a multiplicative constant. A complete discussion of this technique is given in Reference 15.

The technique is applied by first setting up the equilibrium equations for each joint with the load applied at that joint. A set of equilibrium equations result when this process is applied to the entire structure. Each equation of the set will have the following form:

$$T_1 a_{12} + T_2 a_{21} + \ldots + F_1 = 0 \tag{4.4}$$

The set of equations can be written in matrix form as:

$$\begin{bmatrix} a_{11} & a_{12} & - - - - - \\ a_{21} & - - - - - - - \\ - - - - - - - - - \\ - - - - - - - - - \\ a_{11} & - - - - - & a_{ij} \end{bmatrix} \begin{bmatrix} T_1 \\ '' \\ '' \\ '' \\ T_i \end{bmatrix} \begin{bmatrix} F_1 \\ '' \\ '' \\ '' \\ F_i \end{bmatrix} = 0 \tag{4.5}$$

Where: F_i = applied force (lbs)

T_i = tension coefficient $\frac{(lb)}{(ft)}$

a_{ij} = multiplicative constant (ft)

The coefficient matrix, $\left[a_{ij}\right]$, is used to analytically establish the framework stability. The matrix is singular when its determinant is zero and this condition establishes framework instability. If the determinant is non-zero, then the framework is stable.

If this evaluation is pursued as in Reference 15, it is possible that a more simple approach to framework stability can be made. The key is the order of the framework (order is defined as the number of joints lying in each transversal place of connection); if the order is odd, then the framework is unstable; if even, it is stable.

There are other methods whereby stability can be evaluated for a self-contained framework and which provide the designer with a means of adding members to achieve stability. One method of Reference 16 involves using the relationship:

$$m = 3j - 6 \tag{4.6}$$

where: m = number of members

j = number of joints

If this relation is satisfied, then the necessary condition for stability is achieved.

4.4.2 MULTIPLE STAGE FRAMEWORK

It is possible to determine the number of joints for a system which contains (S) stages by:

$$j = n\,(S + 1) \tag{4.7}$$

where n = order of the framework (number of joints at the transvere plane) and S = number of stages. The number of members (m) is:

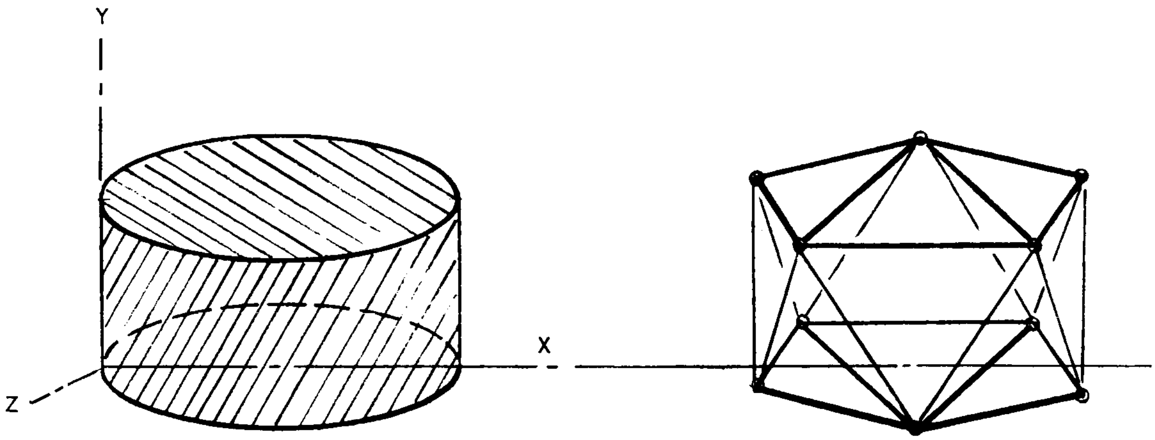
$$m = n\ (3\ S + 1) \tag{4.8}$$

If these equations (4.7) and (4.8) are substituted into equation (4.6), a final relationship results which states that frameworks which have an order (n) greater than 3 will be unstable.

It is possible, however, to stabilize frameworks of higher order by imposing certain constraints. These may take the form of a bulkhead which can be rigid (Figure 4-12a) or semi-rigid (Figure 4-12b). A rigid bulkhead is one which will prevent warping or motion of the joints. The semi-rigid bulkhead is one which provides stiffness in its plane but does not prevent warping.

In the case of a rigid bulkhead, the transversal plane on which it is located becomes rigid, preventing any distortion on that plane. However, if the order of the framework at other transverse planes is even, then distortion and instability can occur. If the order is odd, then the frame is stable.

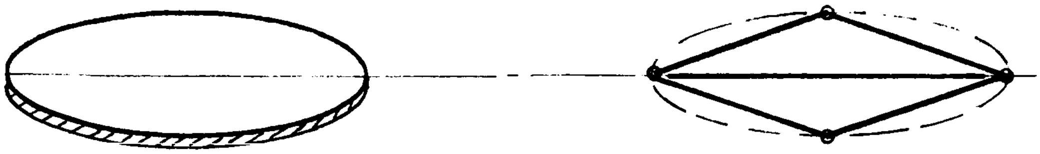
In the case of a semi-rigid bulkhead the bulkhead can be regarded as representing additional members that are connected at the joints. This provides a means to stabilize the framework since the transverse plane is stabilized by the triangulation formed by the additional members. Furthermore, it is desirable for the framework to have an odd order (n). An even order, two-stage framework which has been stabilized



RIGID BULKHEAD
SOLID PLATE

FRAMEWORK EQUIVALENT
TO A SOLID PLATE

a. RIGID



SEMI-RIGID BULKHEAD
THIN PLATE

FRAMEWORK EQUIVALENT
TO A THIN PLATE

b. SEMI-RIGID

FIGURE 4–12 FRAMEWORK STABILITY CONSTRAINTS

by the introduction of additional members at the transversal plane is shown in Figure 4-13.

It is possible to extrapolate this case to any multiple stage framework to show stability. One can conclude that the multiple stage space framework is stable if its extreme planes are made semi-rigid by triangulation.

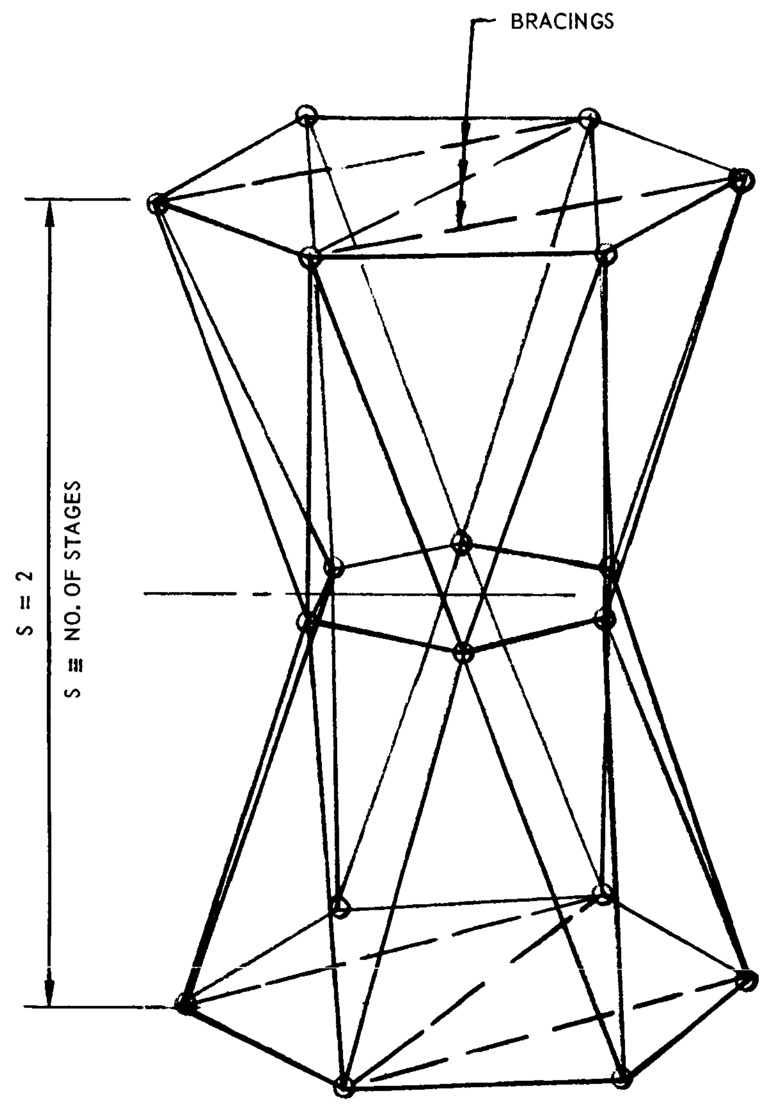
The following conclusions for multiple stage continuous space frameworks are drawn:

1) Self-contained frameworks with one rigid bulkhead are kinematically stable if the order is odd; if unstable, it is shown in Figure 4-14.

2) Self-contained frameworks with both extreme planes possessing semi-rigid bulkheads are kinematically stable regardless of the order.

3) Any portion of a multiple stage continuous space framework between two semi-rigid bulkheads is kinematically stable regardless of order.

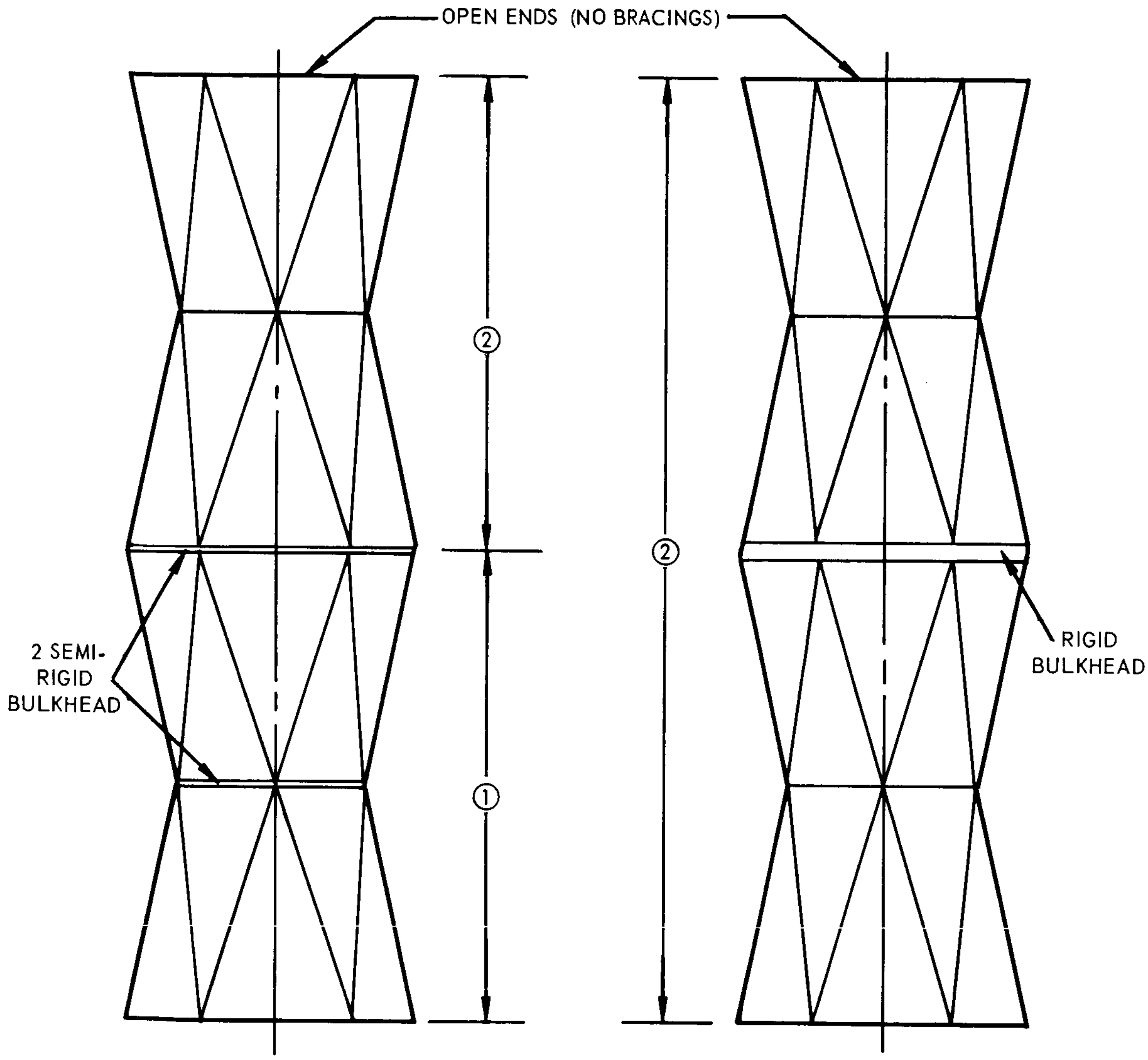
These conclusions show that a framework of variable geometry structure can be made stable by additional struts at the ends of the structure or at intermediate points. The stability criterion shows that it can be accomplished with little additional weight or few members.



NOTE:

WITH ENDS BRACED THE STRUCTURE IS KINEMATICALLY STABLE.
WITHOUT BRACINGS THE STRUCTURE IS KINEMATICALLY UNSTABLE.

FIGURE 4–13 STABILIZED EVEN-ORDER TWO-STAGE FRAMEWORK



NOTE ① THIS PORTION IS KINEMATICALLY STABLE FOR N = ODD OR N = EVEN. N ≡ NUMBER OF CHORDS.

② THIS PORTION IS KINEMATICALLY STABLE FOR N = ODD, AND KINEMATICALLY UNSTABLE FOR N = EVEN.

FIGURE 4-14 STABILIZED MULTIPLE-STAGE FRAMEWORKS

4.5 WEIGHT STRENGTH STUDIES

An investigation was made to establish some of the weight-strength parameters important in the selection of a rigid frame VG structure. This investigation evaluated the single-stage (articulated) trapezoidal arch system subject to the independent loading conditions of direct axial load and bending moment. Combined loading conditions were not considered. The deployed arches were considered to be locked in a stable configuration.

Variable geometry configurations which provide 6-, 8-, 10-, and 12-sided base polygons were evaluated.

The study was constrained by the criterion of the buckling strength of the individual members. The minimum weight of the system with this constraint was evaluated. The members were considered to be tubular and the wall thickness was made as small as possible. The limit on the wall thickness is based on the condition that local crippling can take place. Therefore, the load to cause overall general instability of the member was equated to that for causing the localized buckling. The resulting member was regarded as the lightest one.

Two different basic arch forms were considered. That is, the arch which is nonperpendicular to the base ring, Figure 4-15, and the one which is perpendicular, Figure 4-16.

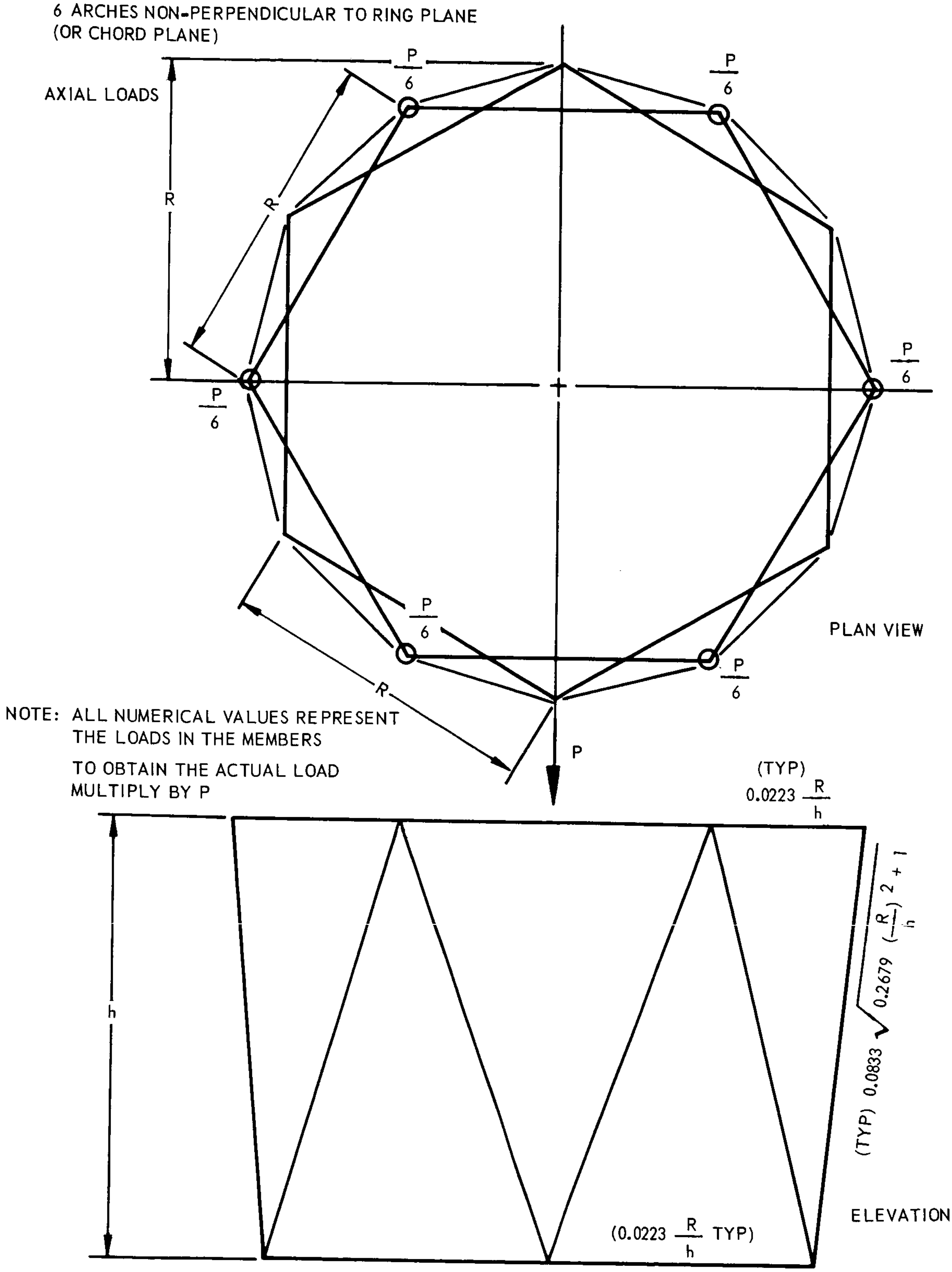


FIGURE 4–15 AXIAL LOADED HEXAGONAL SPACE FRAMEWORK WITH NON-PERPENDICULAR ARCHES

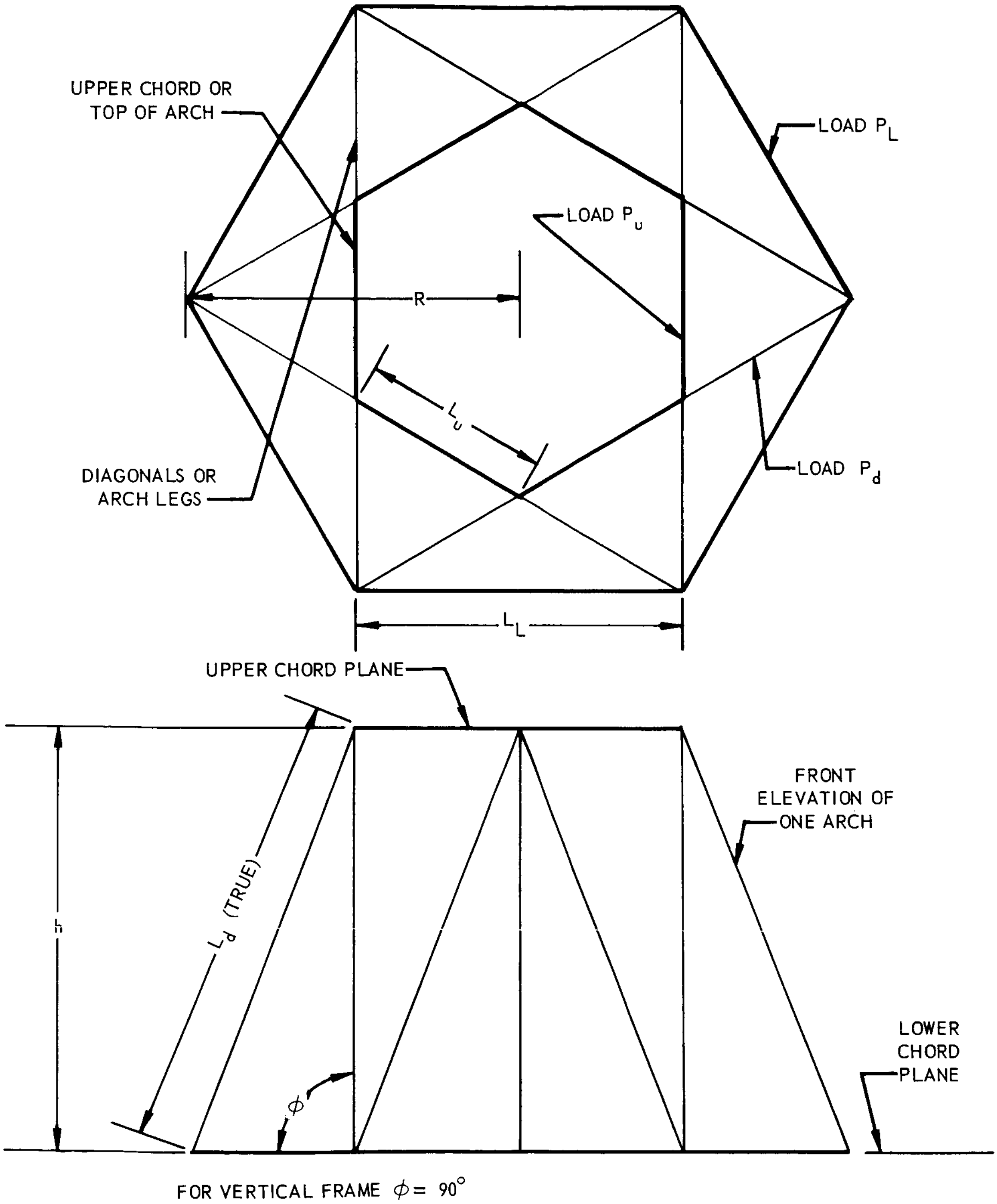


FIGURE 4-16 AXIALLY LOADED HEXAGONAL SPACE FRAMEWORK WITH PERPENDICULAR ARCHES

4.5.1 NON-PERPENDICULAR TRAPEZOIDAL ARCHES

The two evaluated cases are the framework subject to a) an axial load and b) an applied bending moment. Figure 4-15 shows a six-sided polygon base ring with an applied axial load. The numerical values given adjacent to the frame members represent the developed member forces for the loading condition.

The relationships derived in Appendix A for the determination of the optimum weight condition are:

$$\frac{\frac{W_{TOT}}{h}}{C(PR)^{2/3}} = N\left(\frac{R}{h}\right)^{5/3}\left\{\gamma + \beta + \left(\alpha + \left(\frac{h}{R}\right)^2\right)^{7/6}\right\} \tag{4.9}$$

(Nomenclature is given in Appendix A)

This equation is plotted in Figure 4-17 for various base ring polygon configurations.

The case of an applied bending moment is shown schematically in Figure 4-18; the developed loads are given adjacent to the members in the system.

The equation for the total weight evaluation is given as:

$$\frac{\frac{W_{TOT}}{h}}{CM^{2/3}} = N\left(\frac{R}{h}\right)^{5/3}\left\{\gamma + \beta\left(\alpha + \left(\frac{h}{R}\right)^2\right)^{7/6}\right\} \tag{4.10}$$

This was evaluated for several different polygons and the results are shown in Figure 4-19.

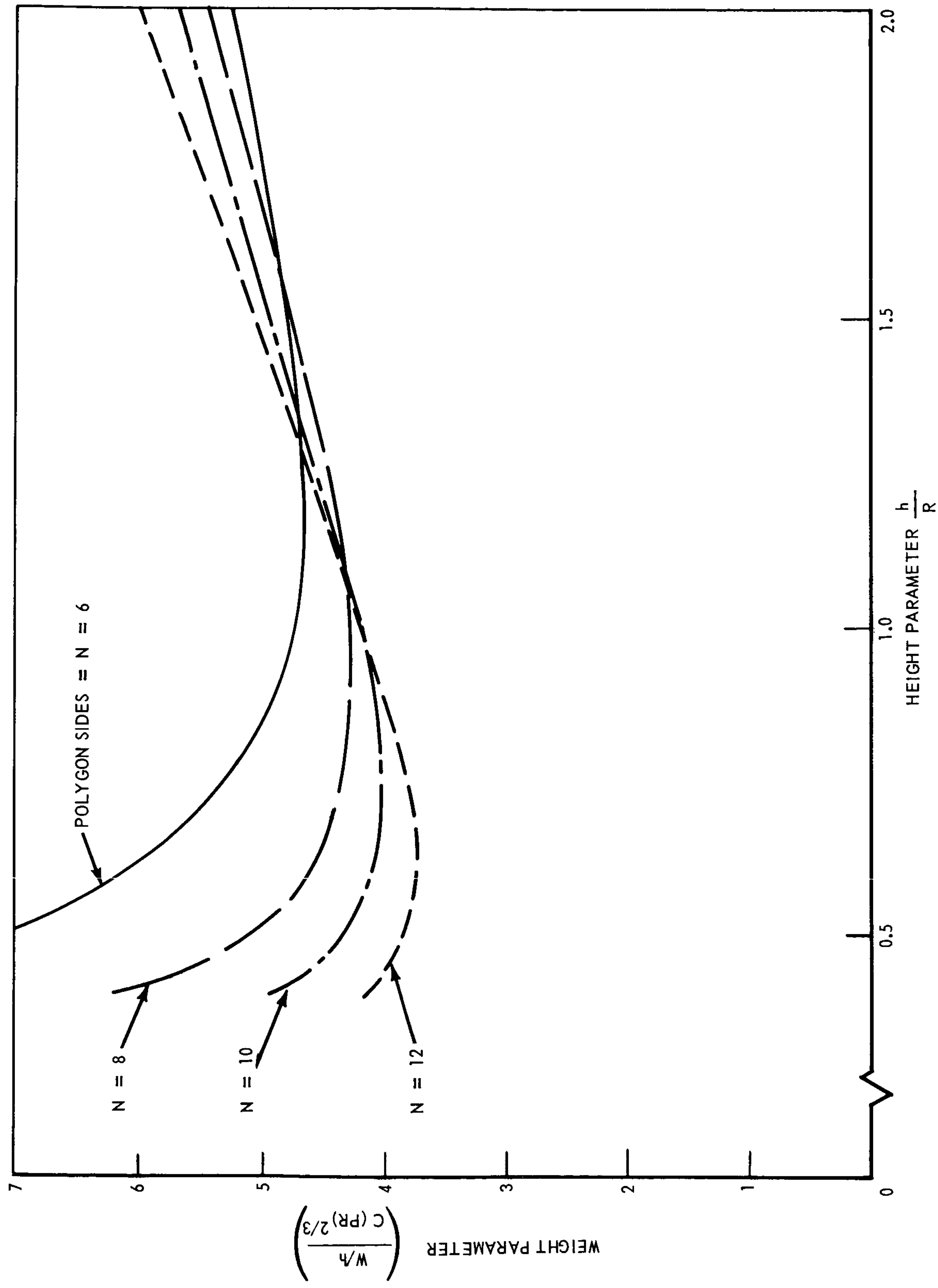


FIGURE 4-17 WEIGHT STRENGTH STUDY. AXIALLY LOADED NON-PERPENDICULAR ARCH FRAMEWORK

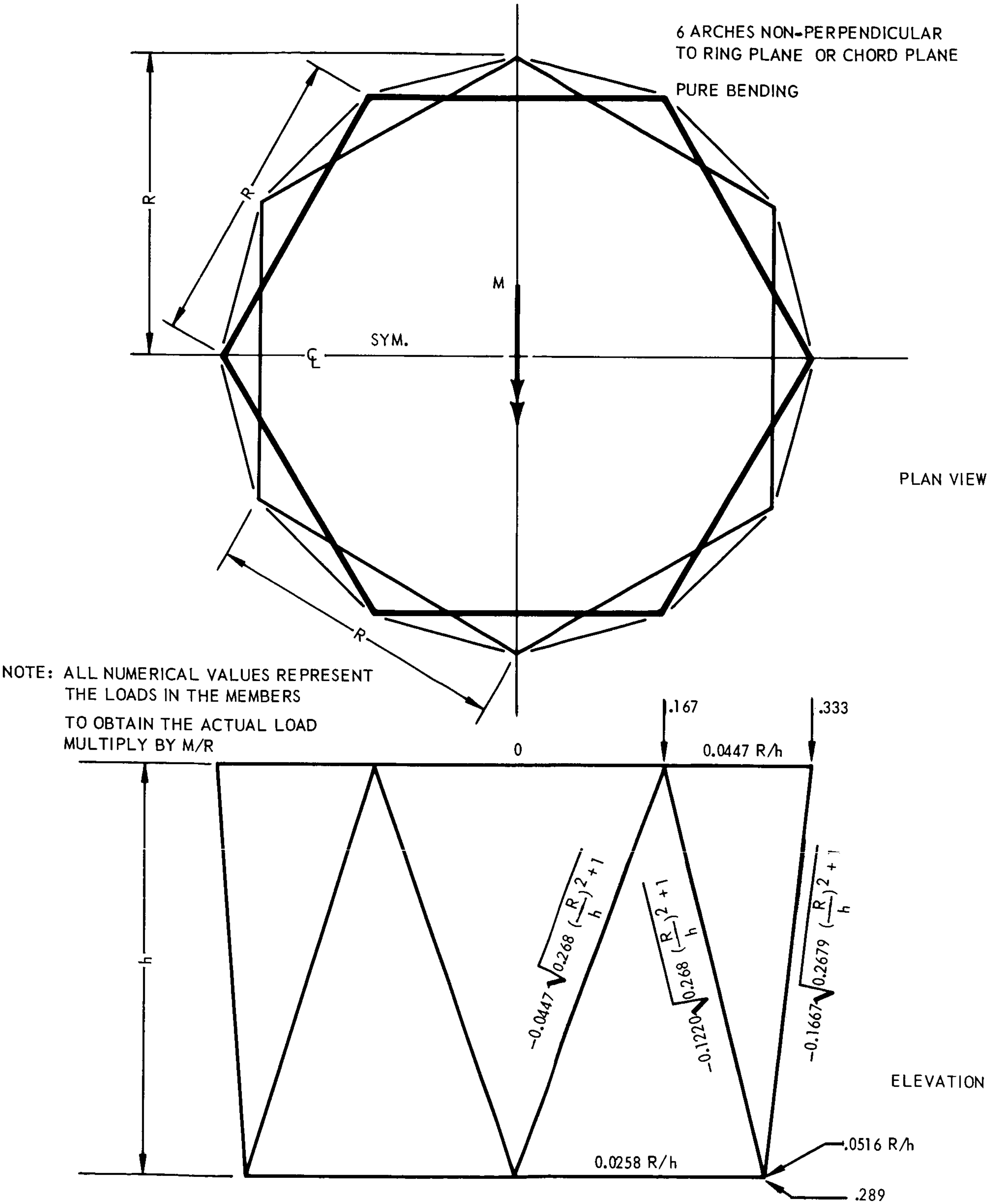


FIGURE 4–18 BENDING MOMENT. HEXAGONAL SPACE FRAMEWORK WITH NON-PERPENDICULAR ARCHES

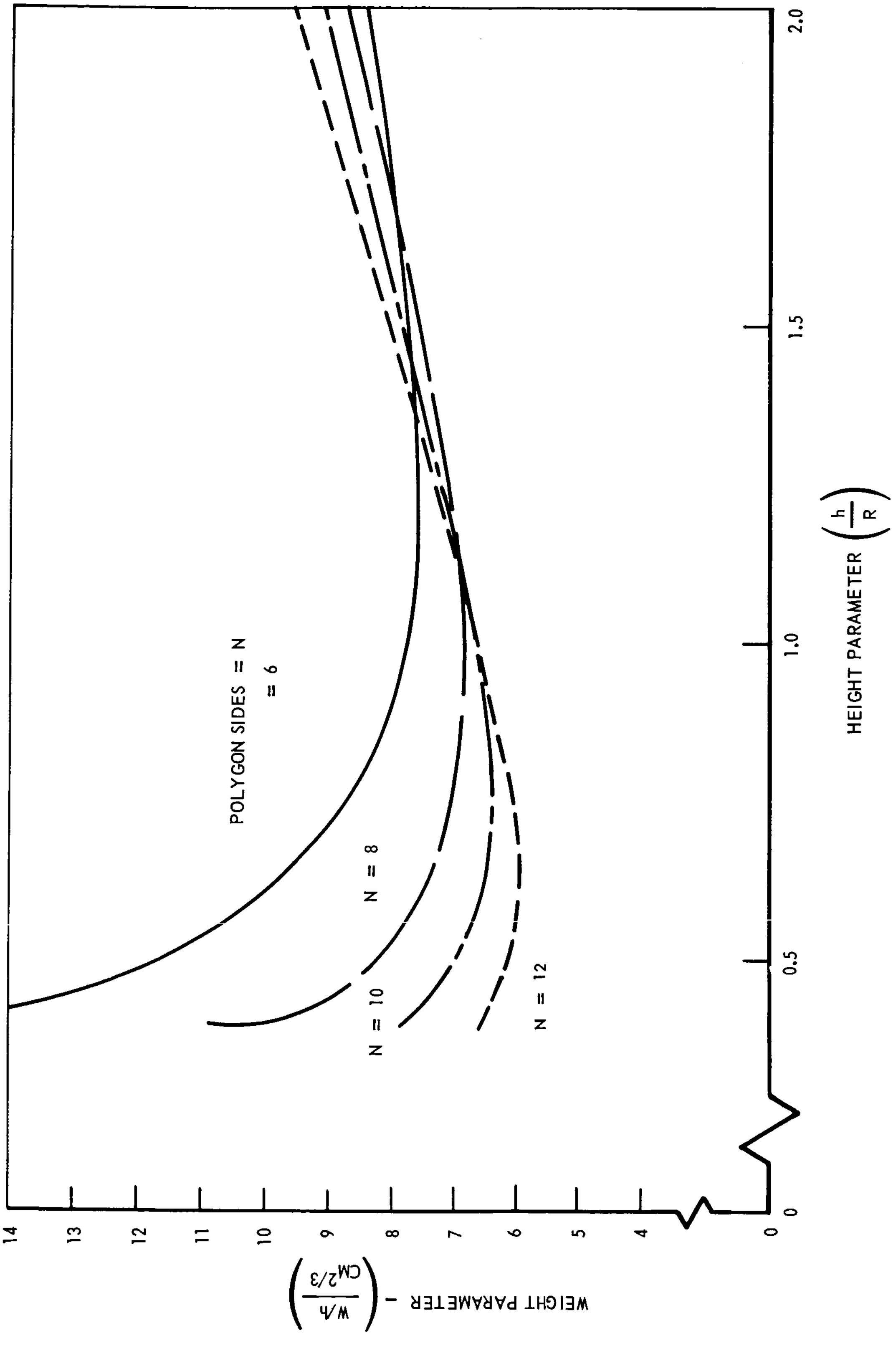


FIGURE 4-19 WEIGHT STRENGTH STUDY. BENDING MOMENT WITH NON-PERPENDICULAR ARCHES

4.5.2 PERPENDICULAR TRAPEZOIDAL ARCHES

This configuration is another in the wide variety of geometries possible in VG structures. The loading conditions considered in the weight strength study are a) an axial load and b) a pure bending moment. This was considered for polygon shapes varying from a hexagon to a dodecagon. The final equations used were identical with Eq. 4.6 and 4.7 of the previous section. The calculational results are shown plotted in Figure 4-20 and 4-21.

4.5.3 CONCLUSIONS

The weight strength study can only be regarded as a partial evaluation highlighting some of the important parameters. Only two loading conditions were evaluated and the minimum weight structure was based on a single parameter; that is, the general buckling localized buckling ratio.

While this criterion is of importance in many structural systems, its significance here is diminished because the VG structure will probably find its greatest application in an environment where the applied loads are nominal. Other parameters which will predominate are the packaging dimensions, system weight, and reliability. An optimized structure for the space environment must consider these parameters as well.

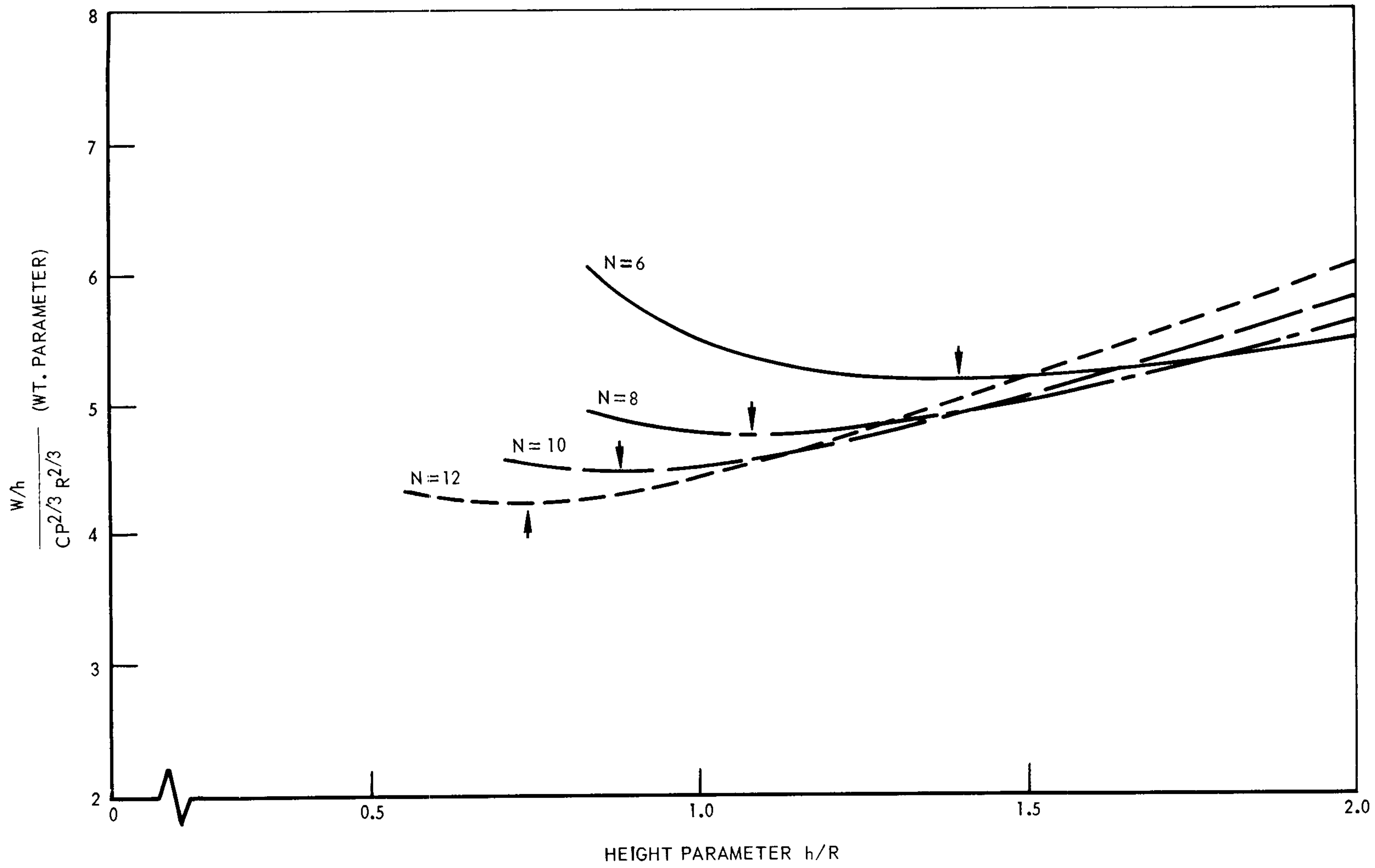


FIGURE 4-20 WEIGHT STRENGTH STUDY — AXIALLY LOADED PERPENDICULAR ARCHES

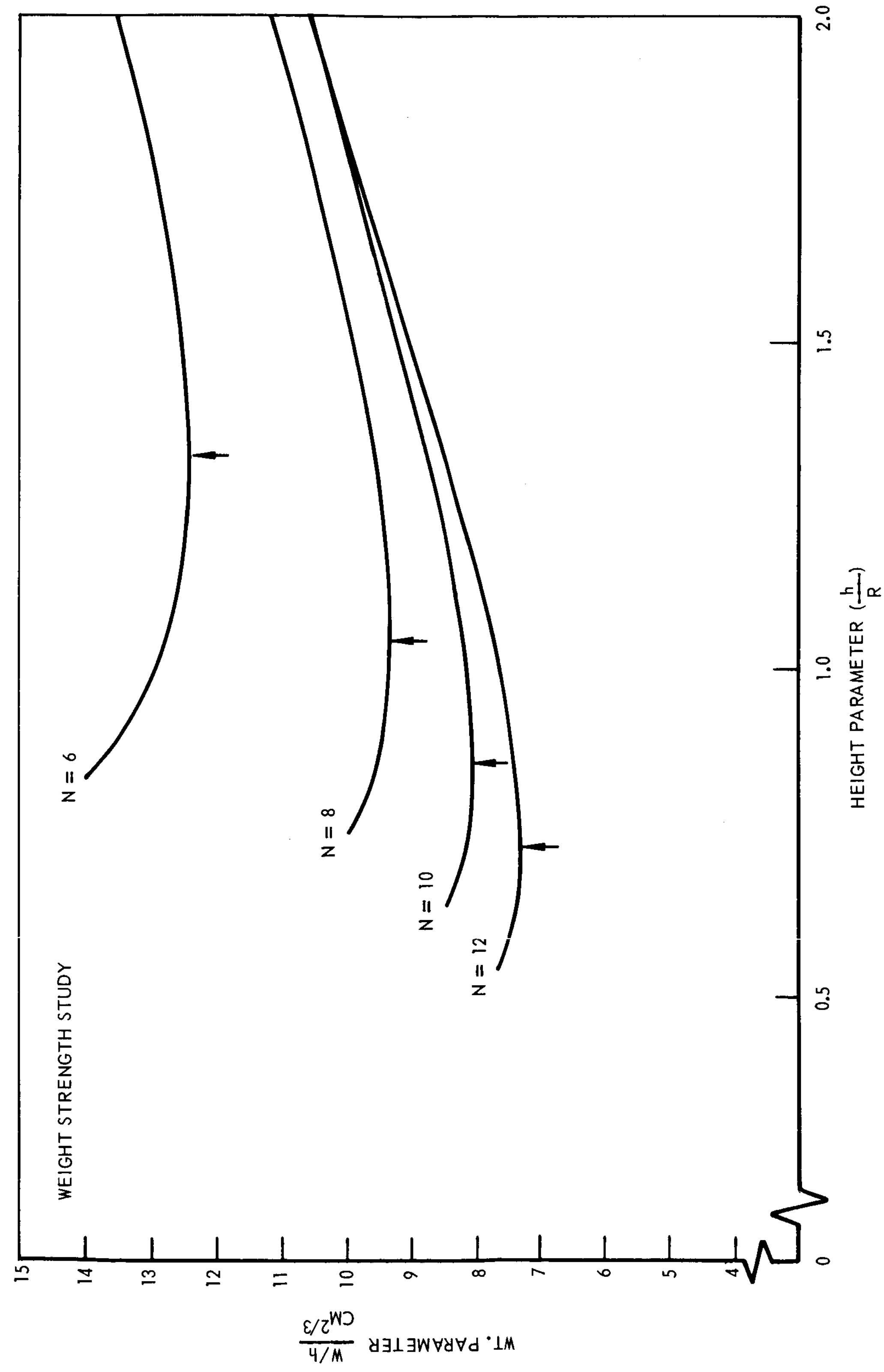


FIGURE 4-21 WEIGHT STRENGTH STUDY — BENDING MOMENT PERPENDICULAR ARCH FRAMEWORK

SECTION V

PANEL STRUCTURES

5.1 INTRODUCTION

Consideration is given here to another VG structure, the panel type. It is made of plane or curved composite panels which can be compacted into a small package and then expanded into an enlarged configuration. The methods of compacting are the familiar techniques of folding overlapping panels or telescoping cylinders and variations of these. Some methods of deployment and actuation are described in Section VII.

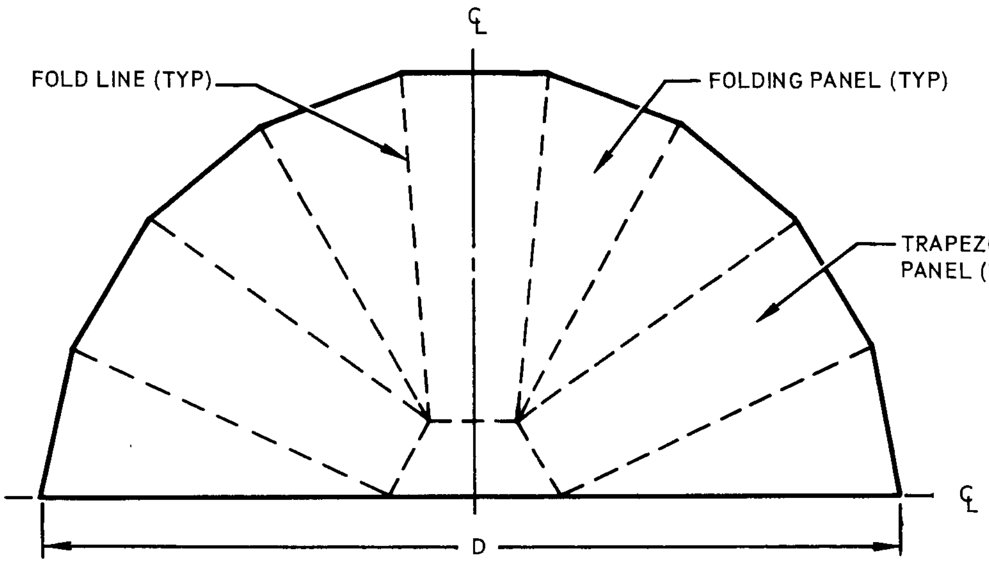
Panel structures are classified in accordance with their deployed configuration; that is (1) planar, (2) singly-curved, and (3) doubly-curved. They are discussed in this order followed, in the latter part of this section, by consideration of integrated panel-and-frame structures.

5.2 PLANE FORMS

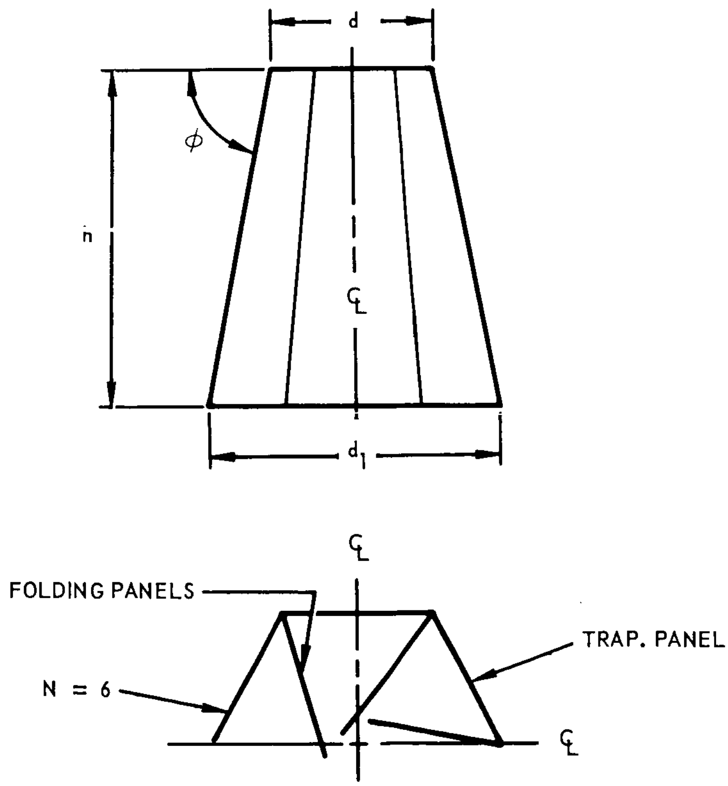
The plane forms which can be used as a panel structure are the disc, strip, and concentric section.

5.2.1 DISCS

The disc is an example of a plane form that may be folded into a cylinder. Such a configuration is shown in Figure 5-1,



a. EXPANDED CONFIGURATION



b. FOLDED CONFIGURATION

FIGURE 5-1 TYPICAL DISC PLANE FORM

where a disc is compressed into a hexagonal truncated cone. This is accomplished by providing fold-lines or hinges in the disc at appropriate locations. It is possible to utilize this structure either in its expanded or folded configuration. If the ultimate use of the structure requires a large planar surface area, then this geometry can be achieved by deploying the cylinder into a disc-like element. The basic cylinder will always take the form of a truncated cone with a varying reference angle, (when $\phi = 90°$ it becomes a right cylinder). This particular case of $\phi = 90°$ may be approached by increasing the number of polygon sides and the number of folds. The triangular sectors (folding panels of the figures) can be made to fold outwardly rather than as shown. This would provide a greater cylindrical internal space but would also increase the outside diameter.

An estimate of the surface area available as a function of height can be obtained from the following equation (the derivation is presented in the Appendix B):

$$\frac{A_e}{\frac{\pi d^2}{4}} = 1 + \frac{4h^2}{d^2 \sin^2\phi} + \frac{4h}{d \sin\phi} \qquad (5.1)$$

where:

A_e = Area of circle circumscribing the expanded polygon

d = Diameter of central ring

h = Height of folded geometry

ϕ = Reference angle of cylinder when folded

This equation is plotted with non-dimensional coordinates in Figure 5-2. It provides an approximation, since it assumes that the expanded, flat, configuration is a circular surface. As the number of sides in the polygon is increased the error obtained from representing the polygon as a circle is decreased. Figure 5-3 provides a means of correcting for the approximation of a polygon by a circle.

5.2.2 STRIPS

Another structure which will develop into a large surface area in the deployed state is shown in Figure 5-4. This particular structure is made up of a large number of panels whose size is determined by the width and height of the center module. The panels are initially compacted against the module sides; upon expansion they extend radially outward. The array of panels is stabilized in the extended position by a hinge-locking mechanism or by telescoping cylindrical rods.

Figure 5-4 shows a planar strip structure which has four sides. It is possible to construct variations of this structure by adding more sides to the polygon to obtain a substantial area development. However an increase in system complexity would undoubtedly accompany this.

A parametric study was made of the expanded area, by using the following equation (which is derived in Appendix B):

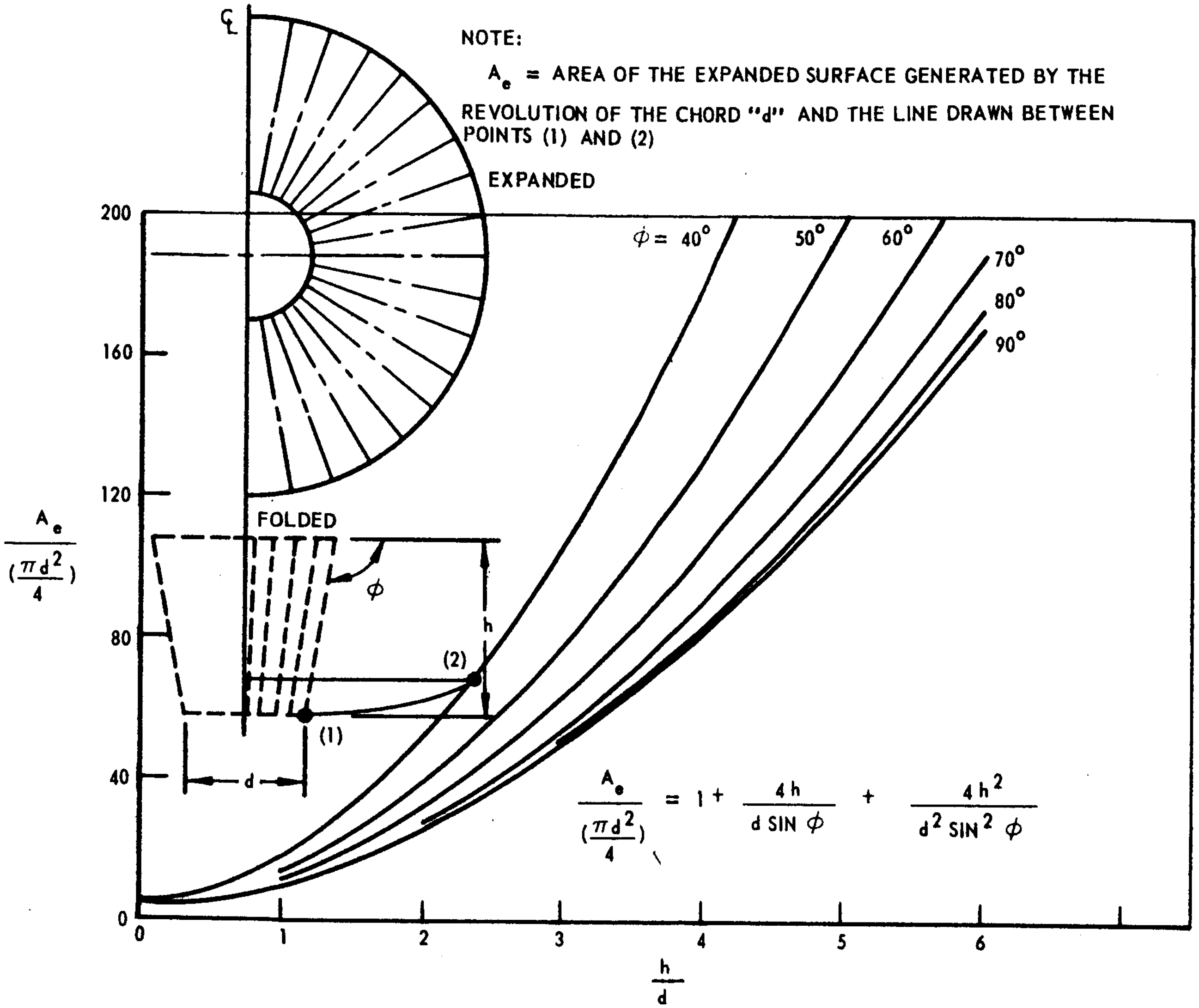


FIGURE 5-2. AREA RATIO FOR DISC PLANAR FORM

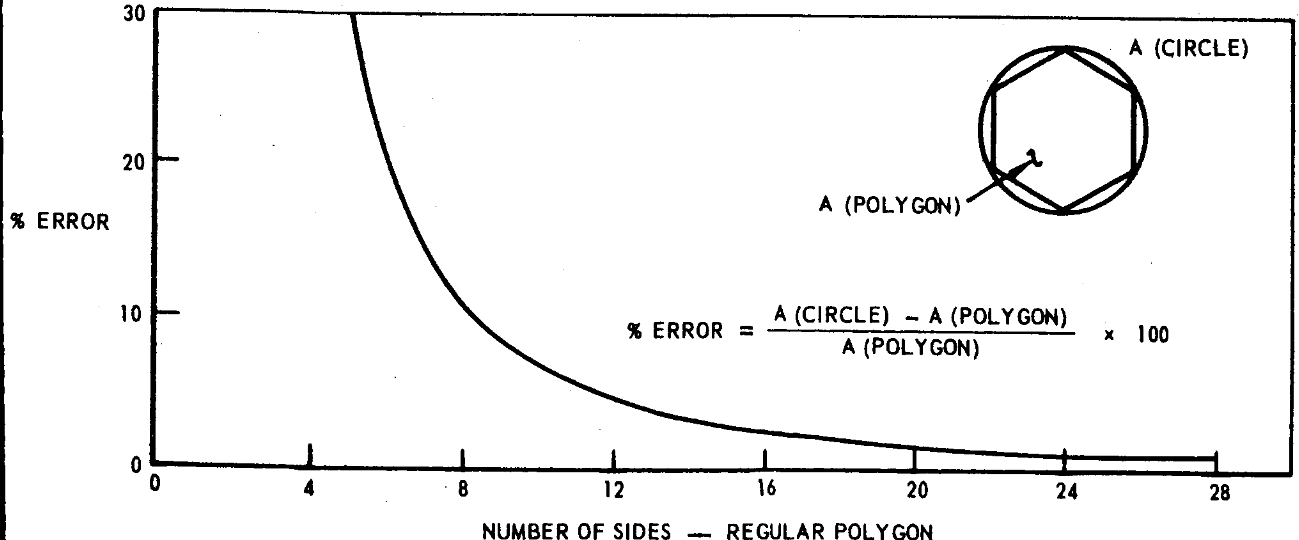


FIGURE 5-3 AREA ERROR BETWEEN POLYGON AND CIRCLE

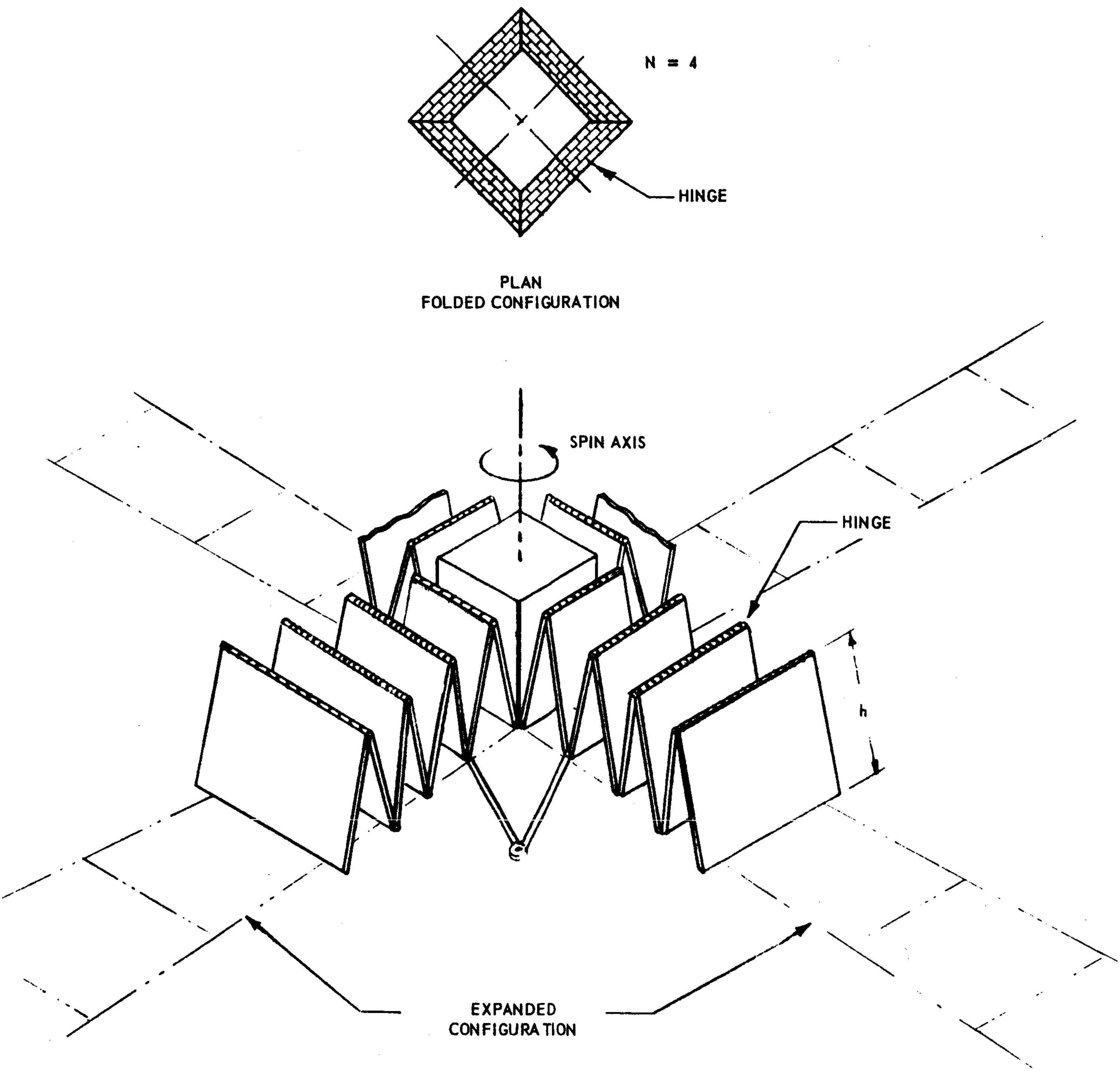


FIGURE 5-4 PARTIALLY DEPLOYED STRIP PLANAR FORM CONCEPT

$$\frac{A_e}{hd} = nN \left[\sin \frac{\pi}{N} - n \left(\frac{t}{d} \right) \tan \frac{\pi}{N} \right] \tag{5.2}$$

where:

A_e = Expanded area

hd = Vertical projected area

n = Panels per side

N = Polygon sides

h = Height of package

d_2 = Diameter of polygon circumscribing circle

t = Thickness of panel

This equation is plotted in Figures 5-5 and 5-6, for two polygons - the hexagon, and the decagon. Varying (t/d_2) ratios were considered. Furthermore, area ratios (deployed area/initial area), are plotted in Figure 5-7. These curves show that a substantial increase in area is possible if the thickness of the panels is small. However, comparison of the curves for a given t/d_2 ratio for various N(polygon sides) show that very little increase in the area ratio occurs as the number of sides increase.

5.2.3 CONCENTRIC SECTIONS

This configuration is basically an umbrella with rigid panels that fold concentrically around an imaginary center post. Figure 5-8 shows the configuration in a compressed state, and follows it through deployment into a fully extended condition. Figure 5-9 suggests details of the concentric section design.

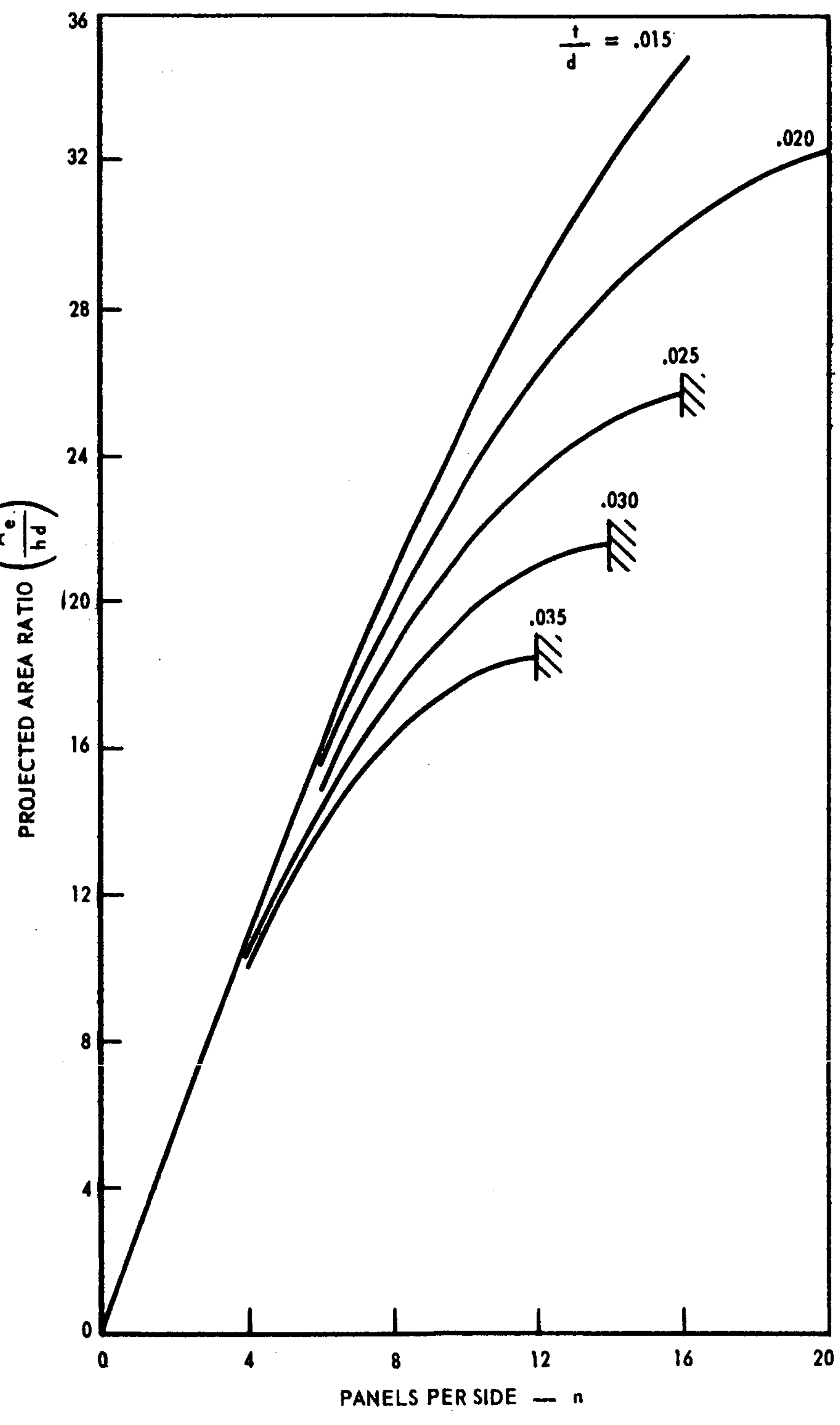


FIGURE 5-5 HEXAGONAL PLANE FORM STRIP

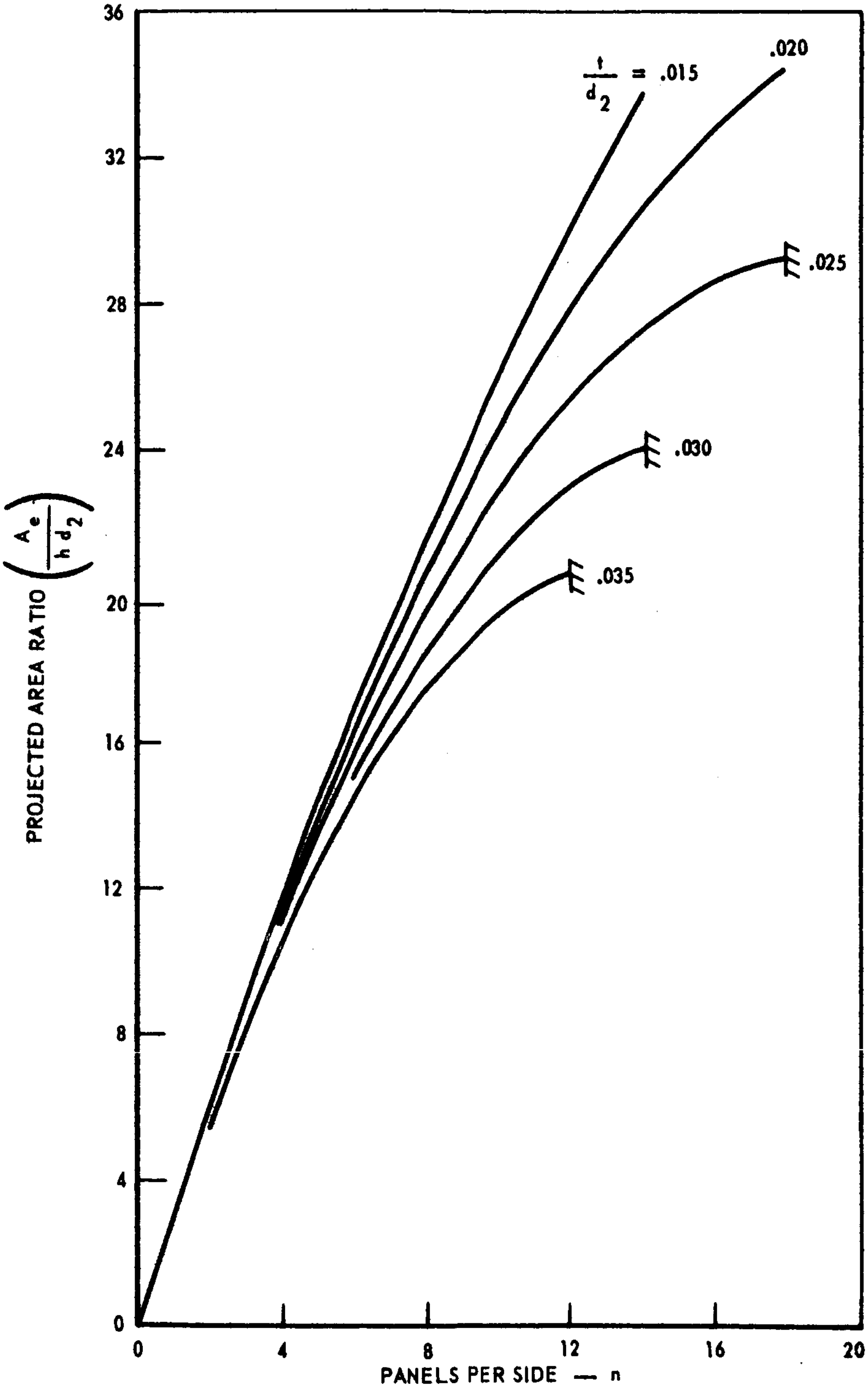


FIGURE 5-6 DECAGONAL PLANE FORM STRIP

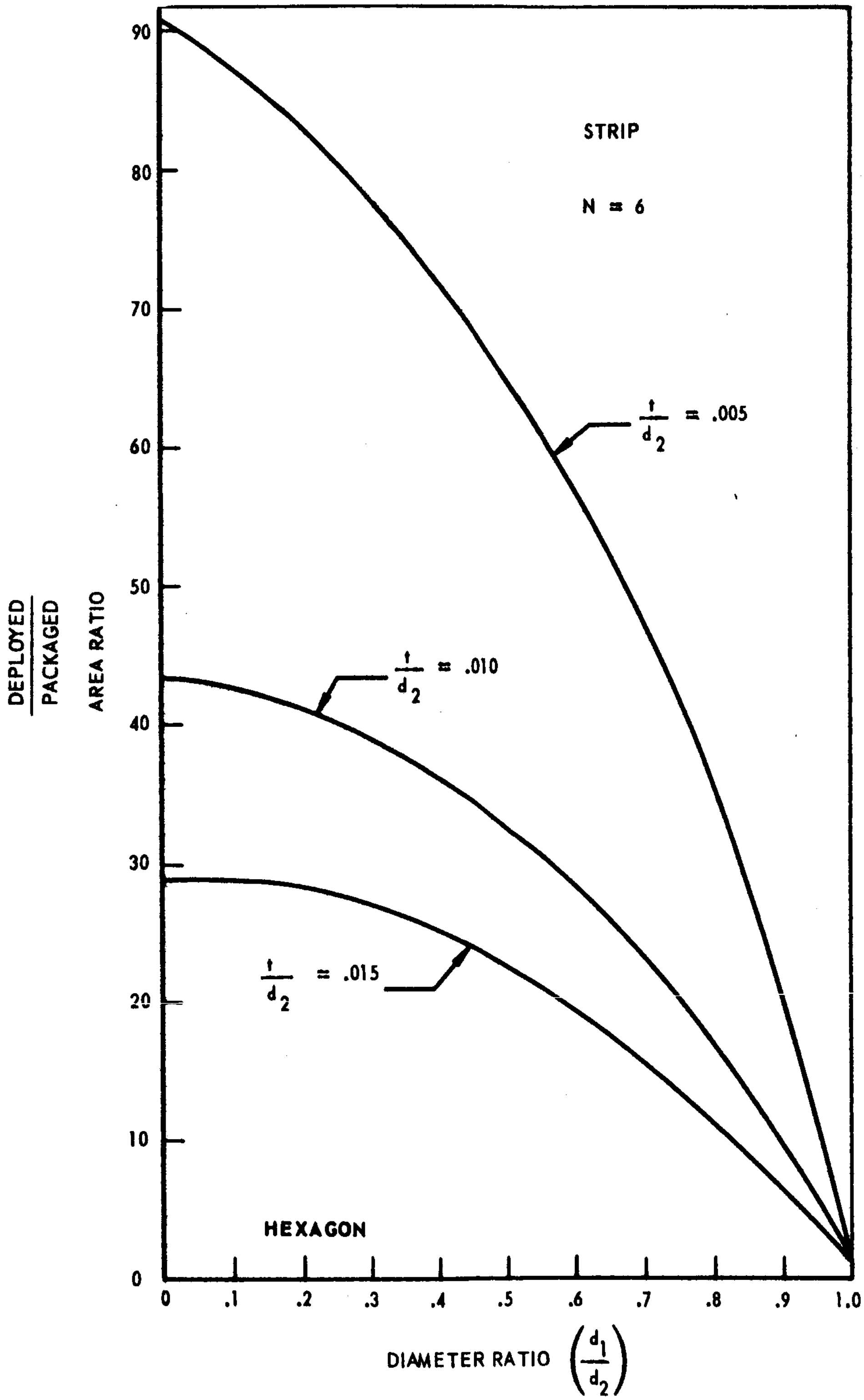
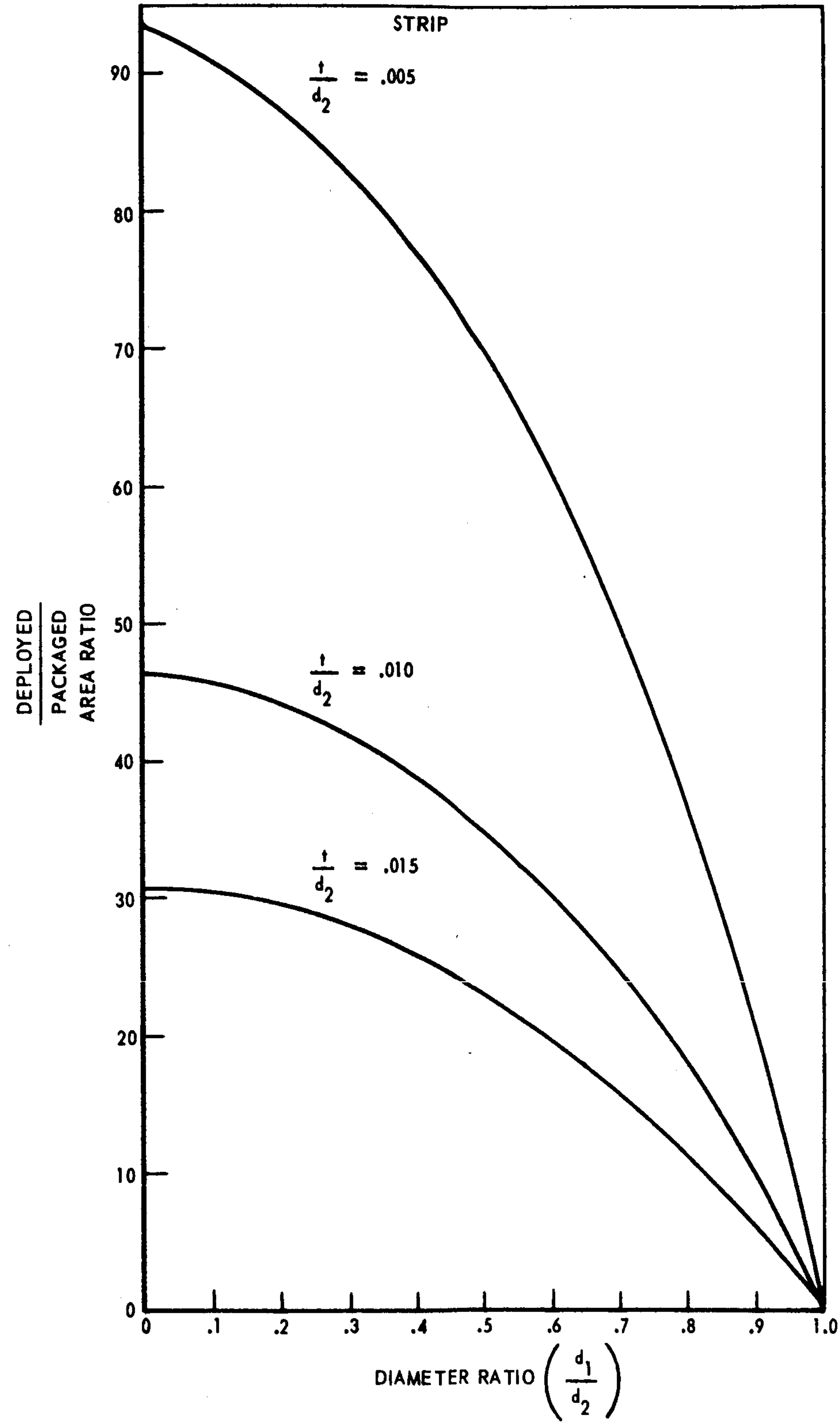


FIGURE 5-7a AREA RATIO FOR POLYGON STRIPS



b. OCTAGON

FIGURE 5-7b AREA RATIO FOR POLYGON STRIPS (Continued)

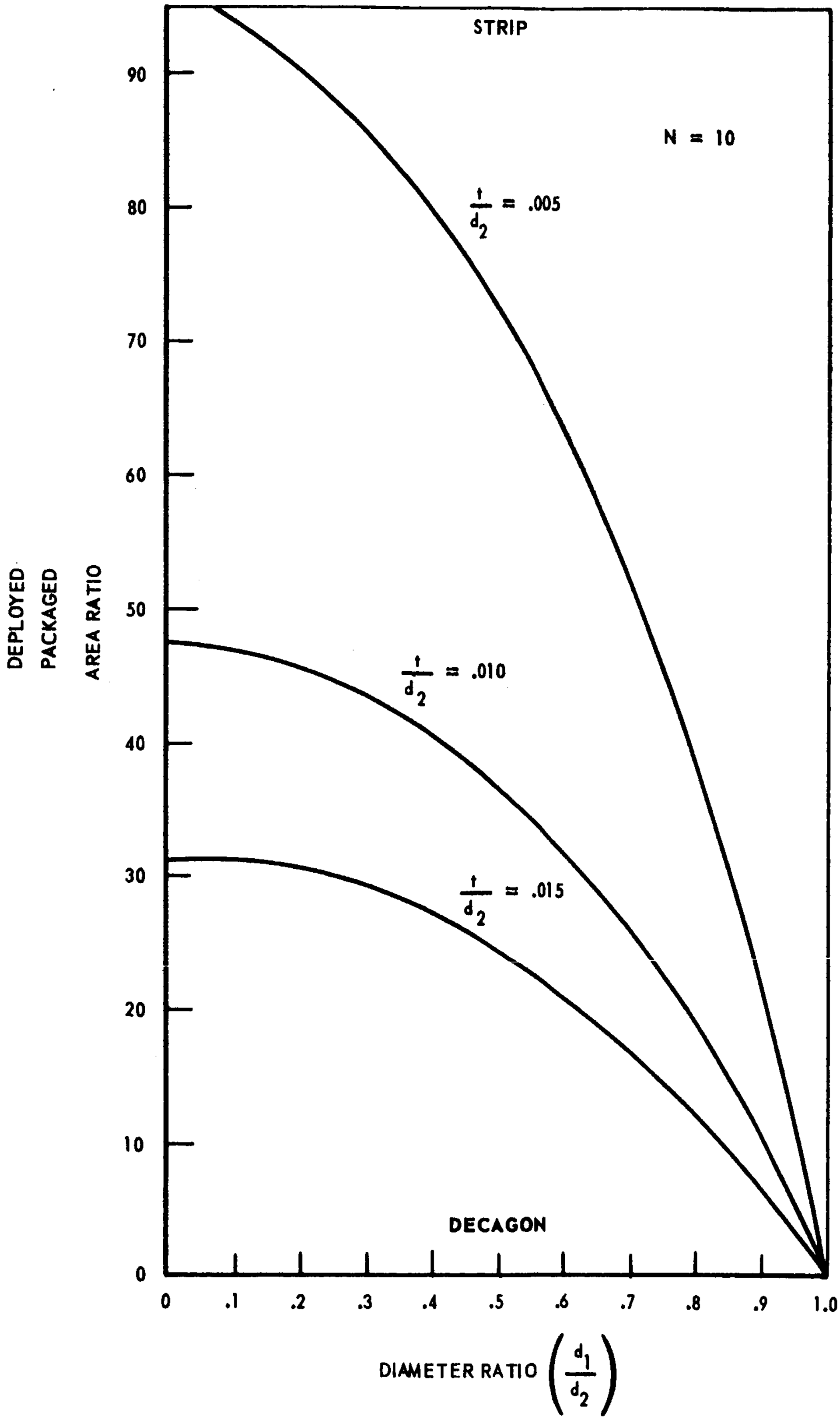


FIGURE 5-7c AREA RATIO FOR POLYGON STRIPS (Continued)

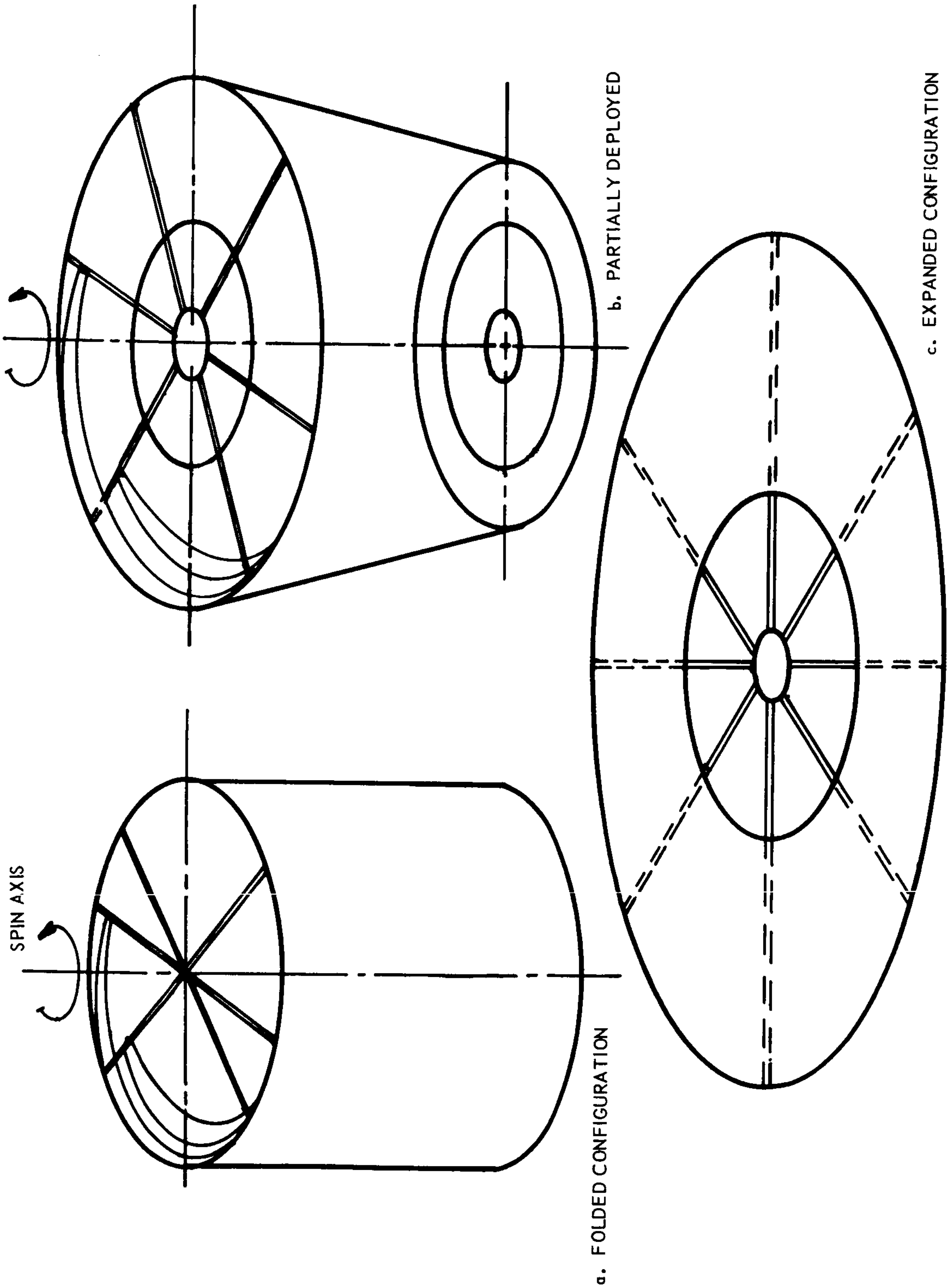


FIGURE 5-8 CONCENTRIC SECTION-PLANAR STRUCTURE

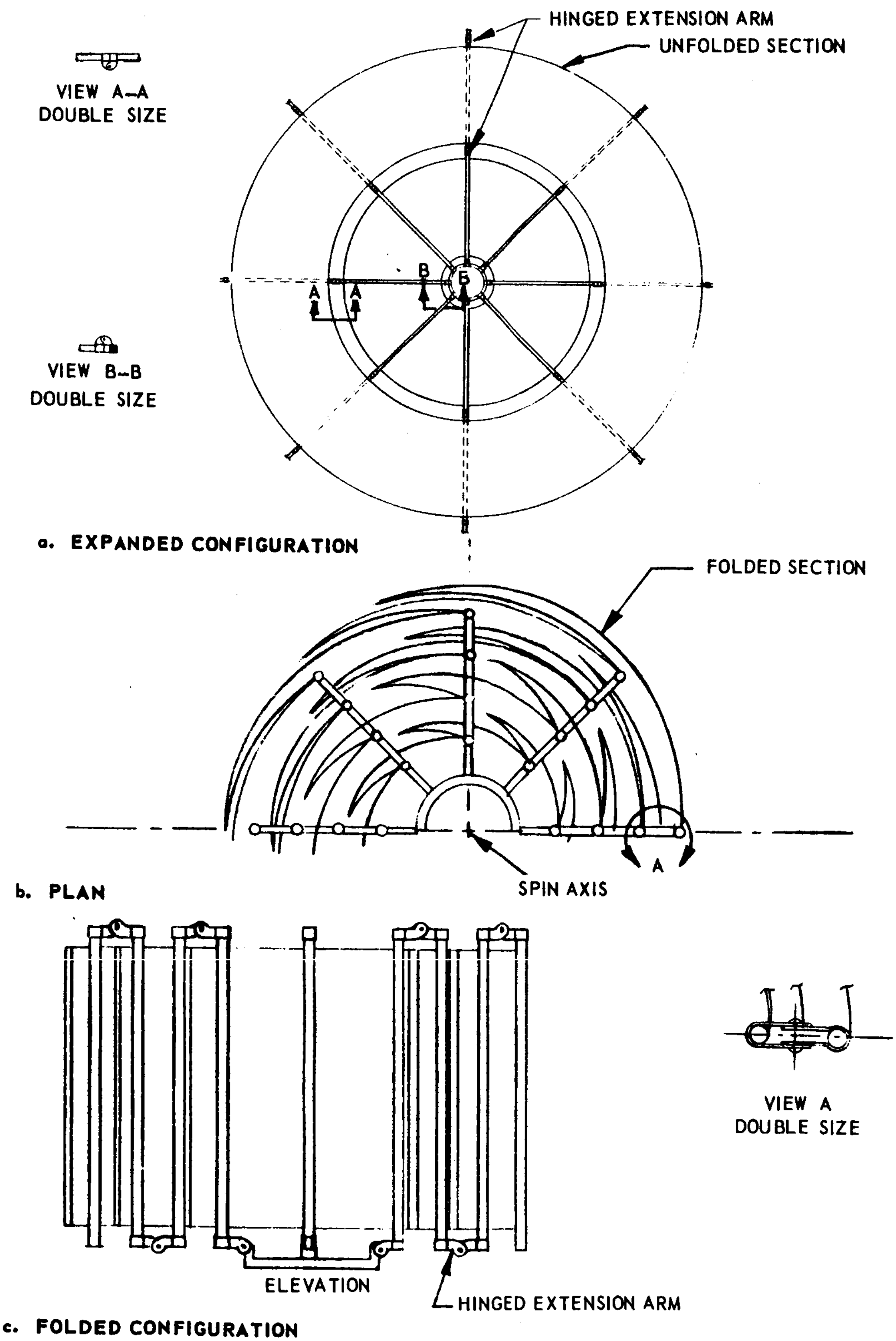


FIGURE 5–9 CONCENTRIC SECTIONS

This structure can be deployed by means of the centrifugal forces developed by spinning of the folded structure. The centrifugal forces cause an outward movement of the panels, along guides, forming the planar structure.

5.3 SINGLE CURVED FORMS

A single-curved configuration is one generated by the revolution of a straight line about another straight line. This section considers telescoping cylinders, as singly-curved VG forms.

5.3.1 Telescoping Cylinders

This concept is identical to the collapsing telescope, where a number of concentric right cylinders or frustums of cones are nested inside adjacent components and extended longitudinally for deployment.

The right circular cylinder is only one of several geometries which will provide a nested set which can be readily expanded into a long cylindrical structure. The following discussion emphasizes the right circular cylinder, but the same principles apply to cylinders with polygonal cross sections.

Figure 5-10 shows a nested set of slightly tapered cylinders. In this design the cylinders are held in place by retaining clips which spring out after the adjacent cylinder has travelled past a certain point. The wall thickness can be varied to provide a means of preventing further slip in the expanding direction. The number of stages in the system will

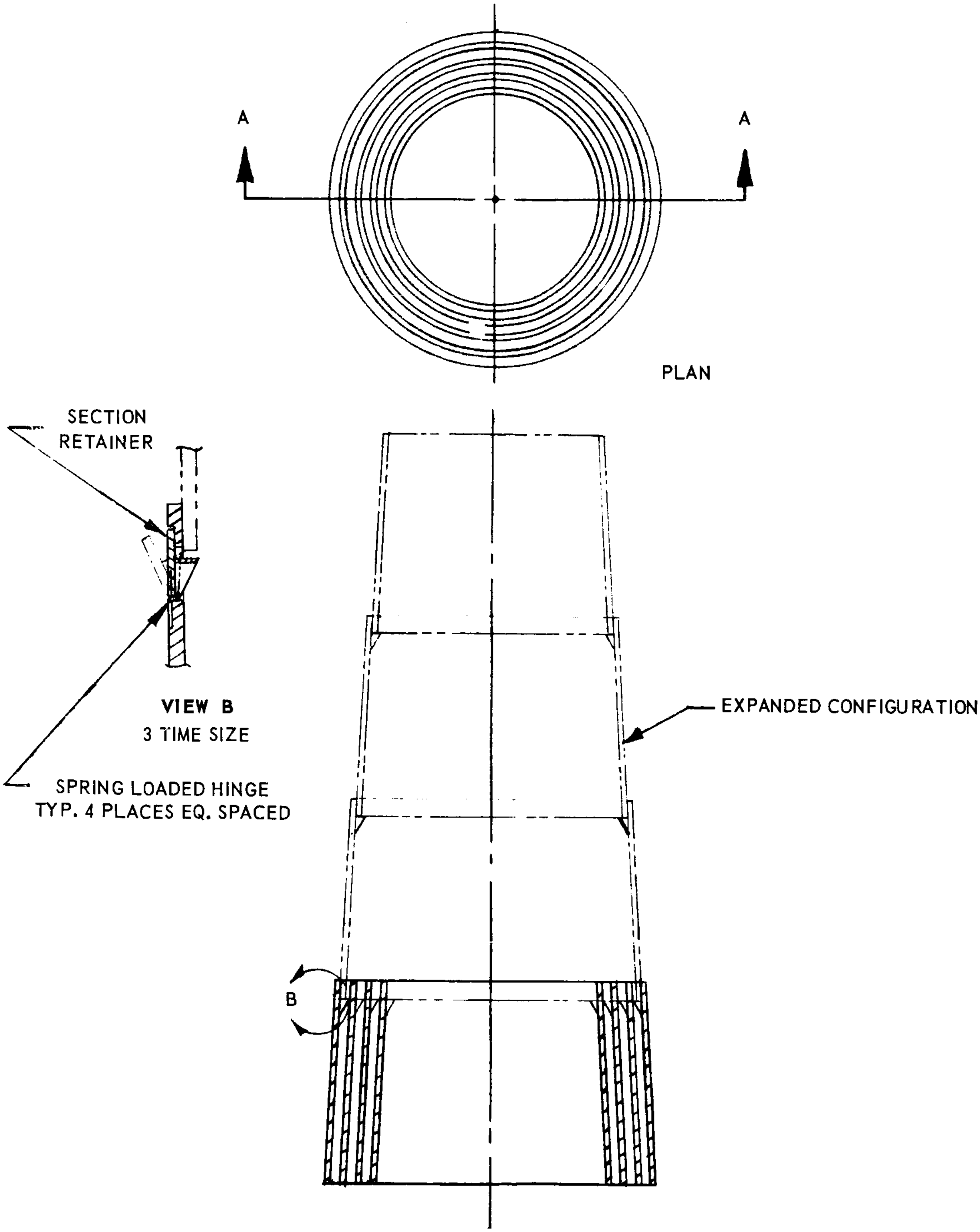


FIGURE 5-10 TELESCOPING CYLINDER — OPEN-END

be primarily limited by the wall thickness of the cylinders and the overall diameter of the outermost component. Other practical considerations come into play here; such as usable volume and actuation techniques, sealing problems, cylinder out-of-roundness, etc., which will influence many design details and ultimately the maximum usable volume. A comprehensive study of the design details and performance tests of telescoping cylinder systems is given in References 17 and 18.

The expression for the area relationship of these cylinders, as derived in Appendix B, is

$$\frac{A_e}{\pi d_2 h} = n \left(1 - (n - 1) \frac{t}{d_2} \right) \qquad (5\text{-}3)$$

where:

A_e = Expanded area

d_2 = Diameter

h = Height of outermost cylinder

n = Number of stages

t = Cylinder wall thickness

The results of this area study are shown in Figure 5-11 for various design configurations.

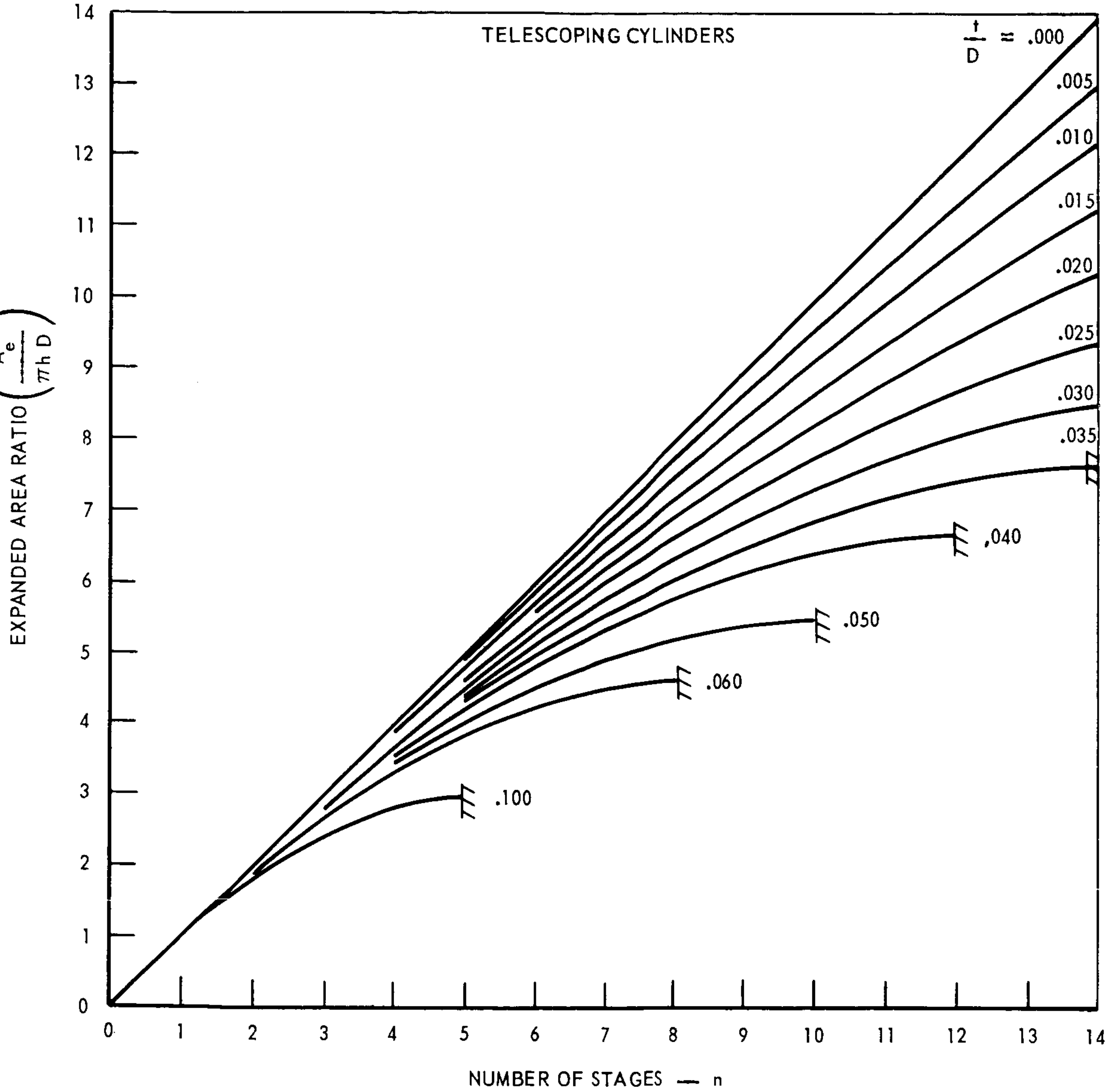


FIGURE 5-11 EXPANDED AREA RATIO VS NUMBER OF STAGES

The expression for the expanded volume is evaluated in Figure 5-12 from the volume (V_e) relationship, derived in Appendix B. This relationship is

$$\frac{V_e}{\frac{h \pi d_2^{\,2}}{4}} = n \left\{ 1 + 2\,(n+1)\,\frac{t}{d_2} \left[\frac{1}{3}\,(2n+1)\,\frac{t}{d_2} - 1 \right] \right\} \qquad (5\text{-}4)$$

and the nomenclature is the same as defined above for Eq. 5-3.

5.4 DOUBLY-CURVED FORMS

A doubly-curved surface is one generated by the revolution of a curve about a straight line. The surface of revolution thus formed may be a hemisphere or a paraboloid, depending upon the generating curve.

5.4.1 Hinged Leaves

It is possible to use the panel geometry in a doubly-curved surface as well as in signly-curved forms. This type of structure involves folding and hinging the panels in a unique manner similar to that indicated by Figure 5-13. The structure shown in this figure is an assembly of curved panels. When expanded, these leaves form a dished geometry resembling a sunflower.

One method of deployment is to provide a center post and auxiliary struts which open like an umbrella. Another method would be a "lazy

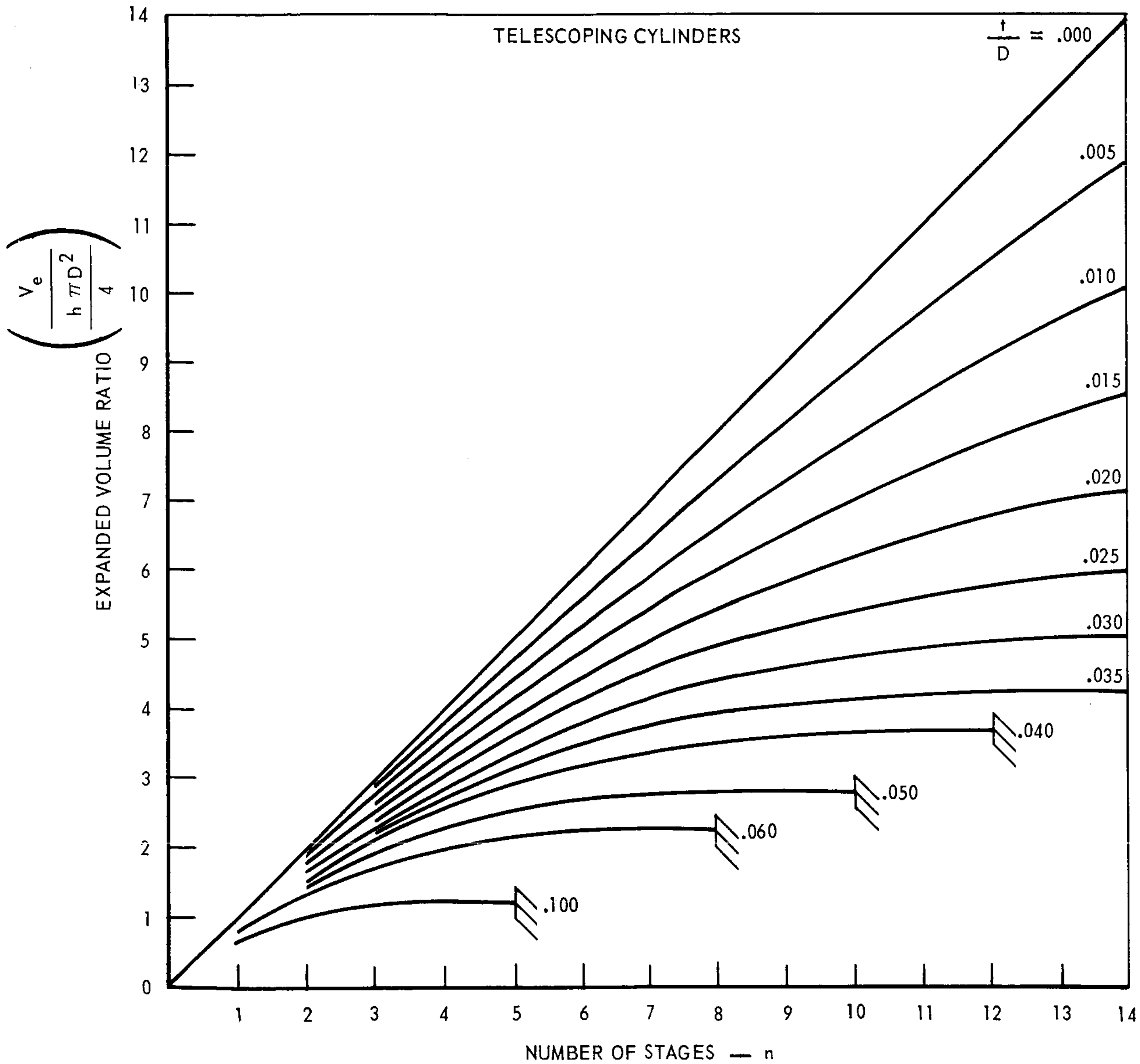


FIGURE 5-12 EXPANDED VOLUME RATIO VS NUMBER OF STAGES

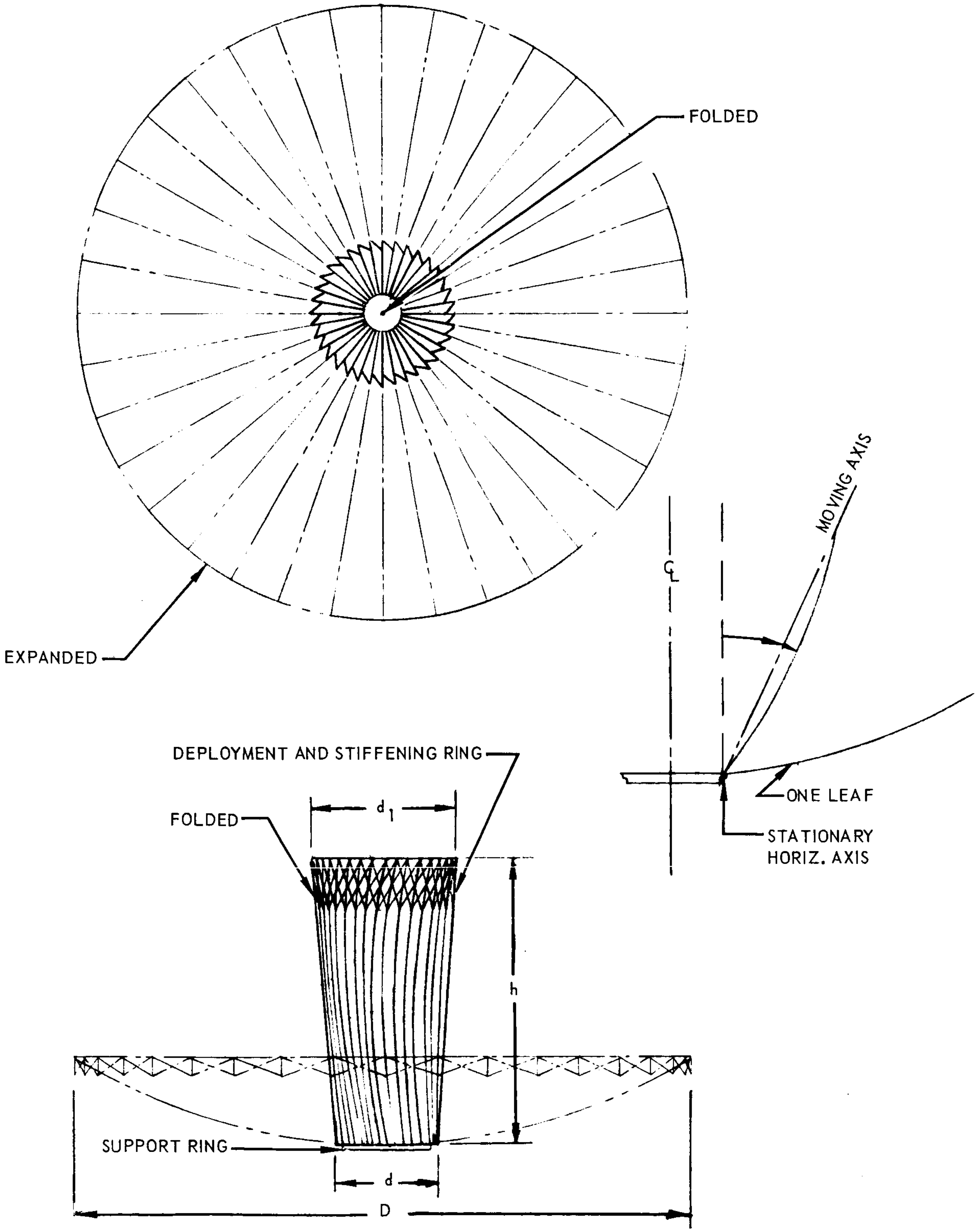


FIGURE 5-13 HINGED LEAVES

tongs" device located at the outer periphery of the dish. These scissors-like devices close upon signal and then cause the outer circumference to enlarge, thus deploying the panels into a dish. The device can be subsequently used to provide stiffening to the structure.

5.5 RADIALLY EXPANDABLE PANEL STRUCTURES

It is possible to combine two panel structures into one integrated unit. One example is shown in Figures 5-14a through d. This structure utilizes the planar expandable structure as the end caps and the folded radially expanding geometry for the longitudinal shell. As the cylinder is extended in a radial direction the ends fold outwardly and provide an enclosure. The result is a complete self-contained unit.

For this particular design configuration it is possible to define limiting values on the end surface area as compared with the entire surface area. This occurs because the ends must fold into the cylinder and overlapping of the folded end sections is not permissible.

The limiting parameters for the expanded size of the structure are the diameter, d_2, and length, L, as shown in Figure 5-15. For a given L and d_2, the maximum expanded diameter, D, is

$$D = L + d_2 \cos \frac{\pi}{N} \tag{5-5}$$

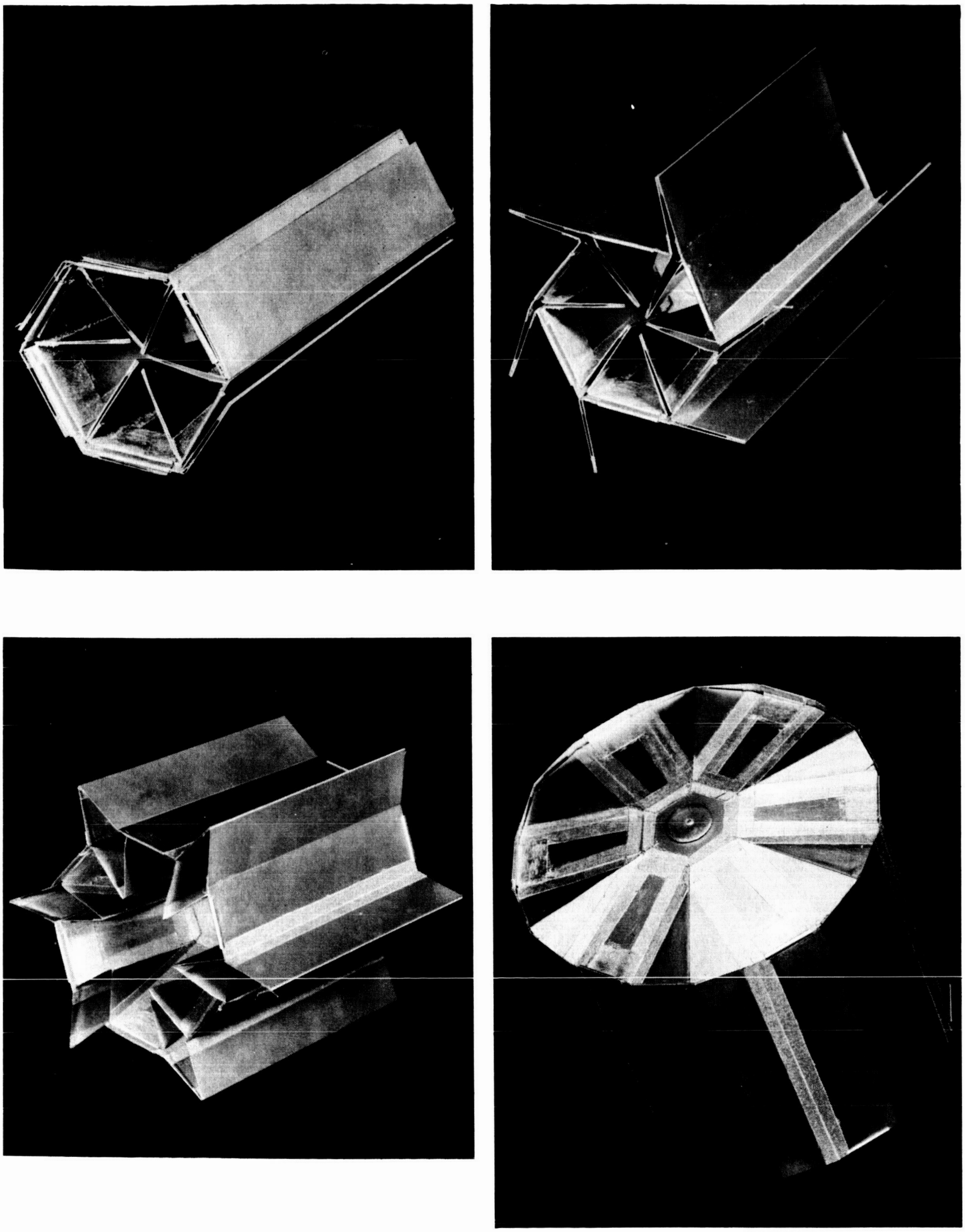


FIGURE 5-14 RADIALLY EXPANDING PANEL STRUCTURE WITH END DISK

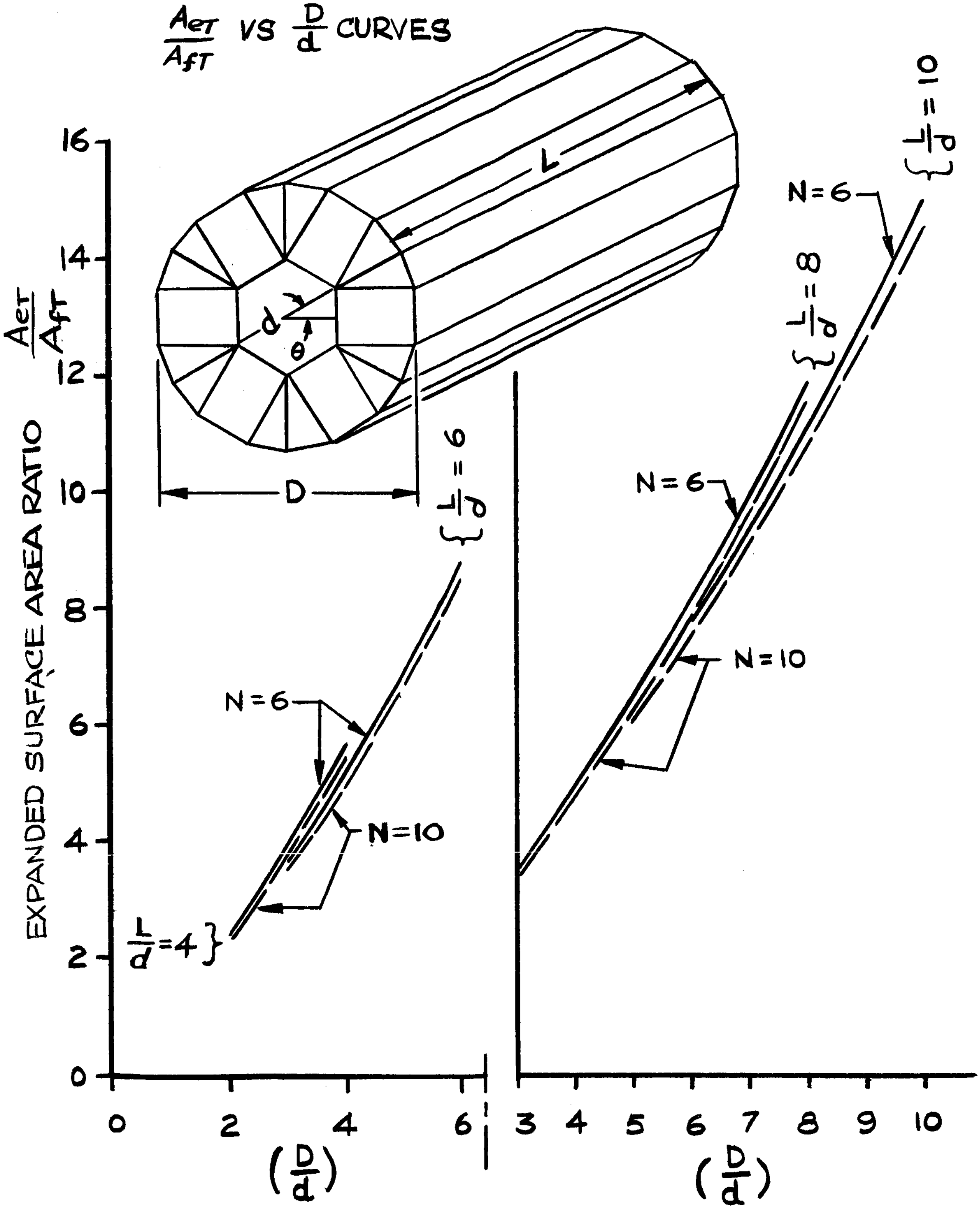


Figure 5-15 Radially Expanded Cylinder, Expanded Area vs Diameter

where N is the number of sides of the polygon in the packaged configuration. The available surface area and volume of the panel structure depend upon D and L.

The relationship of the area ratio parameter is

$$\frac{A_e}{A_f} = \frac{D}{d_2} \quad \frac{\pi}{N \sin \frac{\pi}{N}} \left[\frac{\frac{D}{d_2} + 2 \frac{L}{d_2}}{\cos \frac{\pi}{N} + 2 \frac{L}{d_2}} \right] \tag{5-6}$$

where:

A_e = Total expanded surface area

A_f = Total outside surface area of folded structure

D = Expanded diameter

d_2 = Folded diameter

N = Number of sides of the folded polygon

L = Length of structure

This equation is shown graphically in Figure 5-15.

Several other radially expandable systems were considered from a theoretical viewpoint. The first case is the radially expandable integrated frame-panel structures shown in Figures 5-16 and 5-17. Folding the frame within the panel array limits the amount of radial growth and, therefore, the developed volume and surface area. The maximum possible

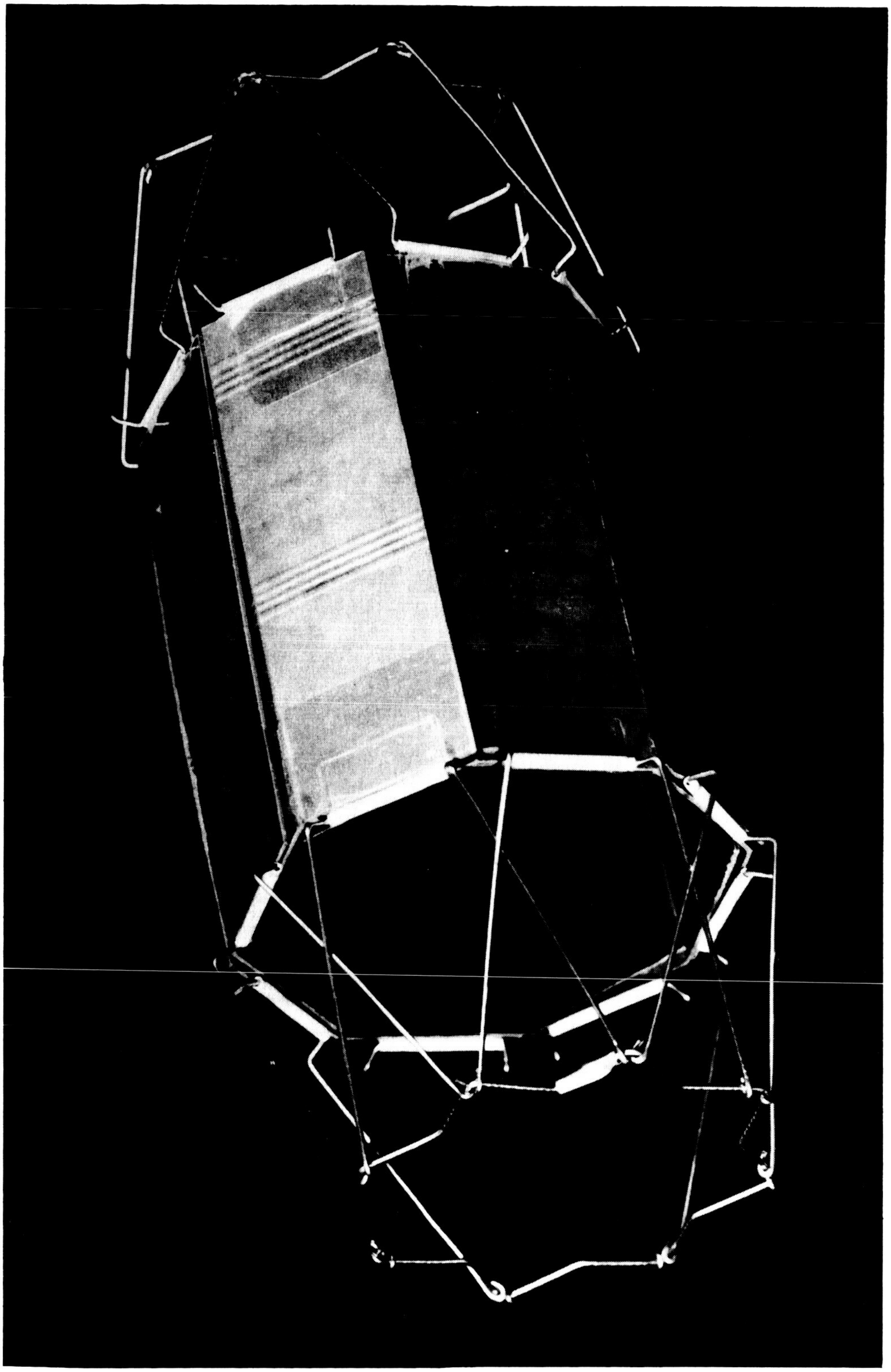


FIGURE 5-16 RADIALLY EXPANDABLE FRAME AND PANEL STRUCTURE, MINIMUM DIAMETER POSITION

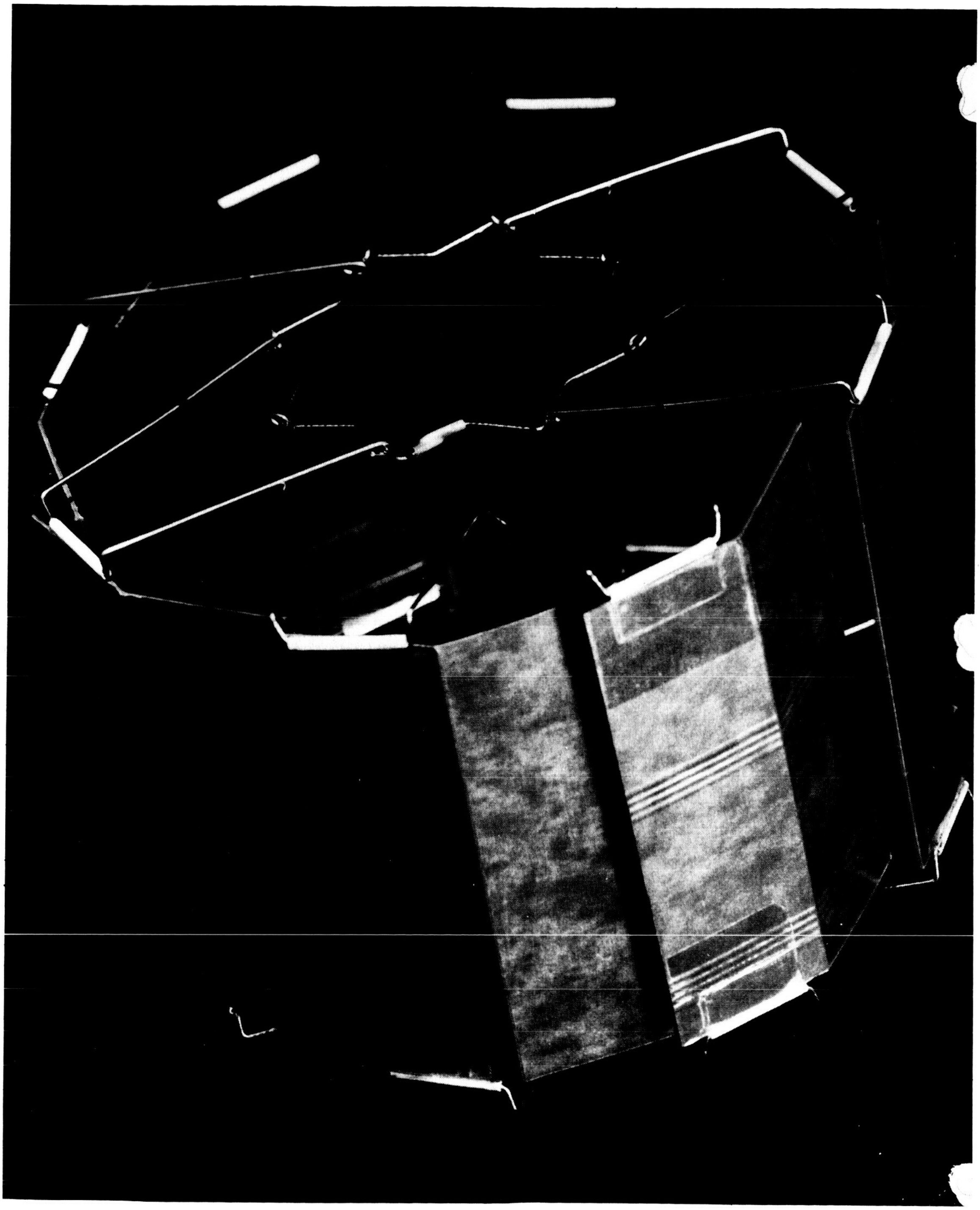


FIGURE 5-17 RADIALLY EXPANDED FRAME AND PANEL STRUCTURE, DEPLOYED POSITION

frame height is the height of the structure (Fig. 2-2). It is shown in Appendix B, that the greatest volume increase which can be expected for a two-fold increase in diameter (if adequate contracted surface material is present) is nine times, the maximum surface area is 3 times.

Several idealized cases where the cylinder contains material which can be used for surface covering, either on the circumference or on all sides of the developed geometry, have been evaluated. The development of the appropriate equations are in Appendix B. The case where the cylinder is radially expanding without end covering gives area and volume ratios as

$$\frac{A_e}{A_i} = \frac{\left[1 - \left(\frac{d_i}{d_2}\right)^2\right]}{4\ {}^{t}/_{d_2}} \qquad (5\text{-}7)$$

$$\frac{V_e}{V_i} = \frac{\left[1 - \left(\frac{d_i}{d_2}\right)^2\right]^2}{4\ {}^{t}/_{d_2}} \qquad (5\text{-}8)$$

where

A_e = Expanded surface area

A_i = Initial surface area

d_1 = Inside diameter of cylinder

d_2 = Outside diameter of cylinder

t = Thickness of covering material

The diameter (d_1) provides a measure of the usable volume contained inside the assembly. This volume can be used for other equipment or additional actuation systems. The outside diameter of the initial package is represented by (d_2).

The case where the volume of contained material is used to cover the ends, as well as the circumference, provides the following volume and area relationships (see Appendix B for derivation)

$$\frac{A_e}{A_i} = \frac{1}{3}\left\{\left(\frac{D}{d_2}\right)^2 + 2\left(\frac{D}{d_2}\right)\right\} \tag{5-9}$$

and

$$\frac{V_e}{V_i} = \left(\frac{D}{d_2}\right)^2 \tag{5-10}$$

where

$$\frac{D}{d_2} = -1 + \left[1 + \frac{\left[1 - \left(\frac{d_i}{d_2}\right)^2\right]}{2\ {}^{t}/_{d_2}}\right]^{1/2} \tag{5-11}$$

The nomenclature is identical to nomenclature in equations (5-7) and (5-8).

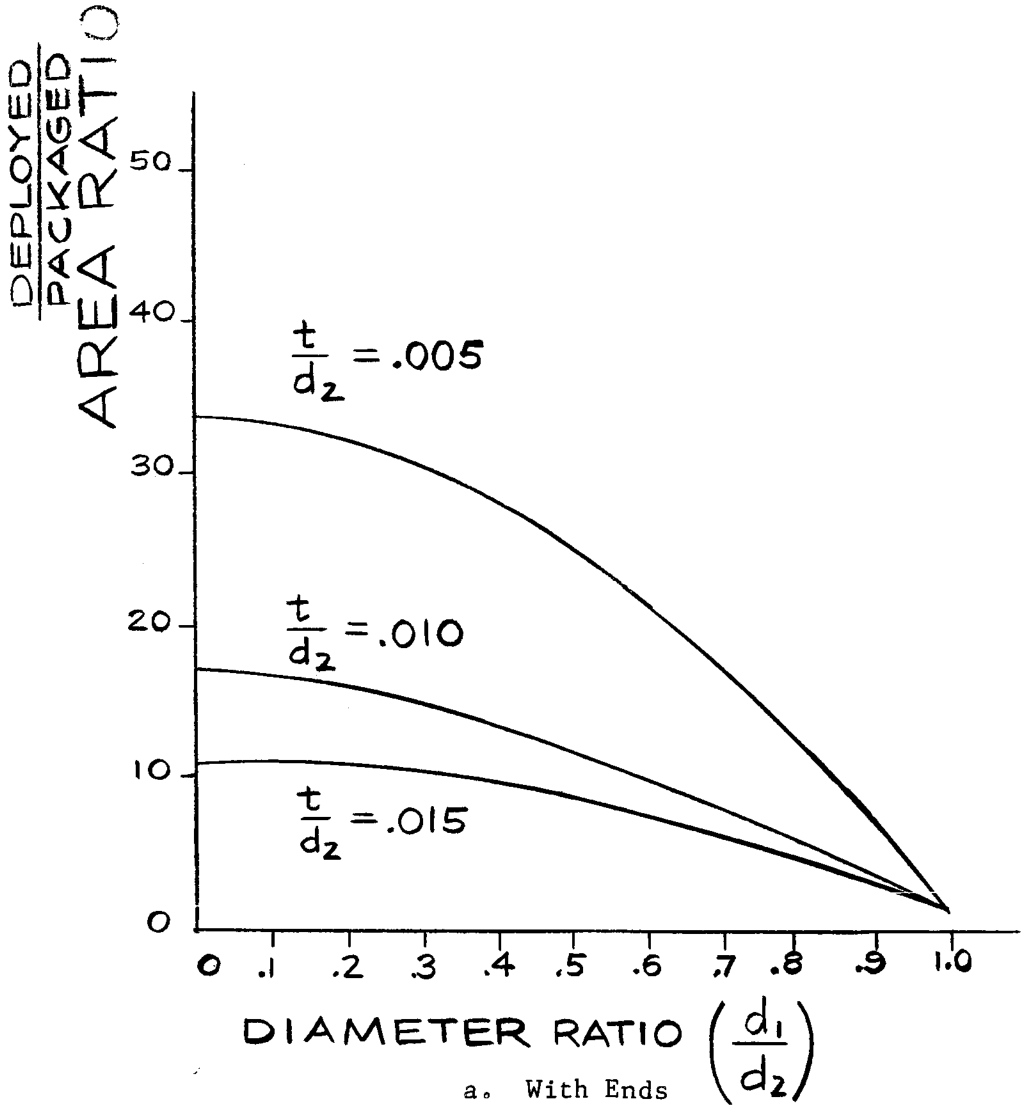
The area and volume parameters were evaluated for the several radially expanding systems and are shown in Figures 5-18 and 5-19. These figures show that substantial volume and area increases are possible when the thickness ratios are small. This is especially true for the case when end surfaces are not developed.

5.6 AXIALLY EXPANDABLE PANEL STRUCTURE

The axially expandable structure incorporates the frame and the panel. Figure 5-20 shows a typical design. The panels are located within rectangular frames, and the frames are hinged to a base ring. The actuation of the panels is accomplished by triangular frames which interlace with the panel frames. In this manner the panels can be moved from a flat position to form a right hexagonal cylinder. This structure can be utilized in a flat position to a cylindrical form which is continuous except at the joints of the panels.

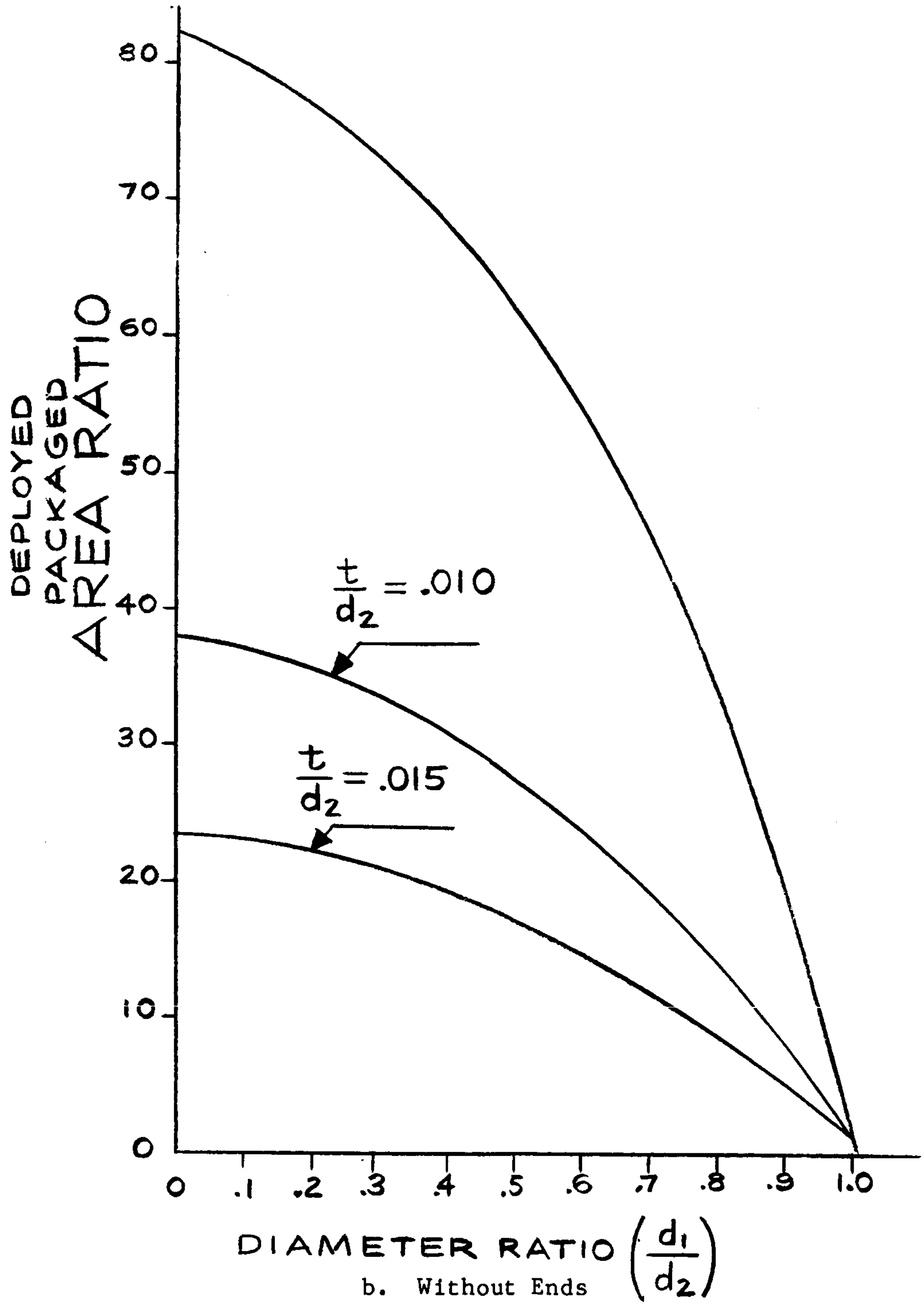
5.7 OVERLAPPING PANELS

The overlapping panel structure makes use of the frame and panel structure in an integrated array. This is shown in Figure 5-17. It is composed of a number of panels, each shaped into a number of plane surfaces. In the folded condition the adjacent panels overlap each other



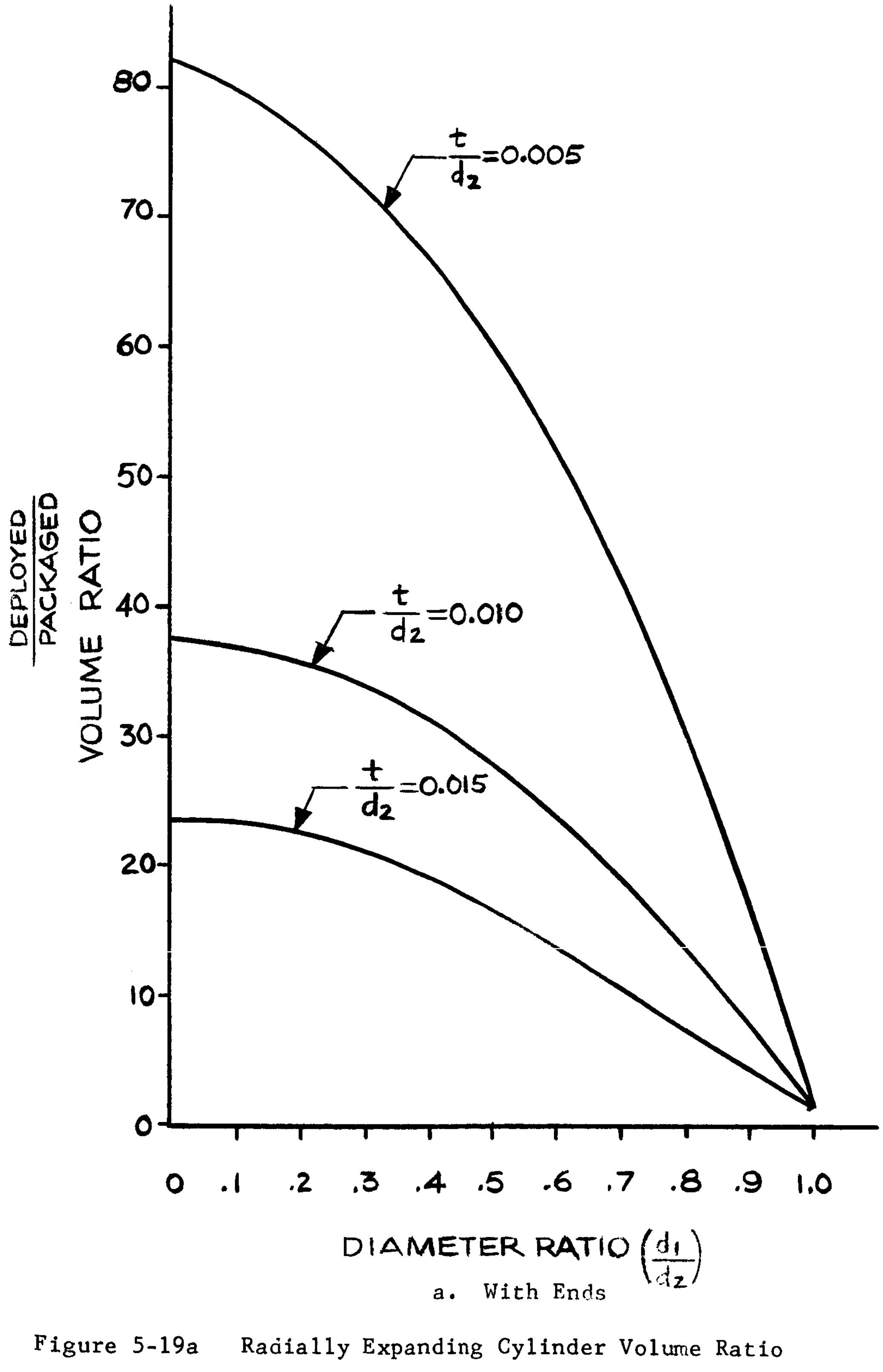
a. With Ends

Figure 5-18a Radially Expanding Cylinder Area Ratio



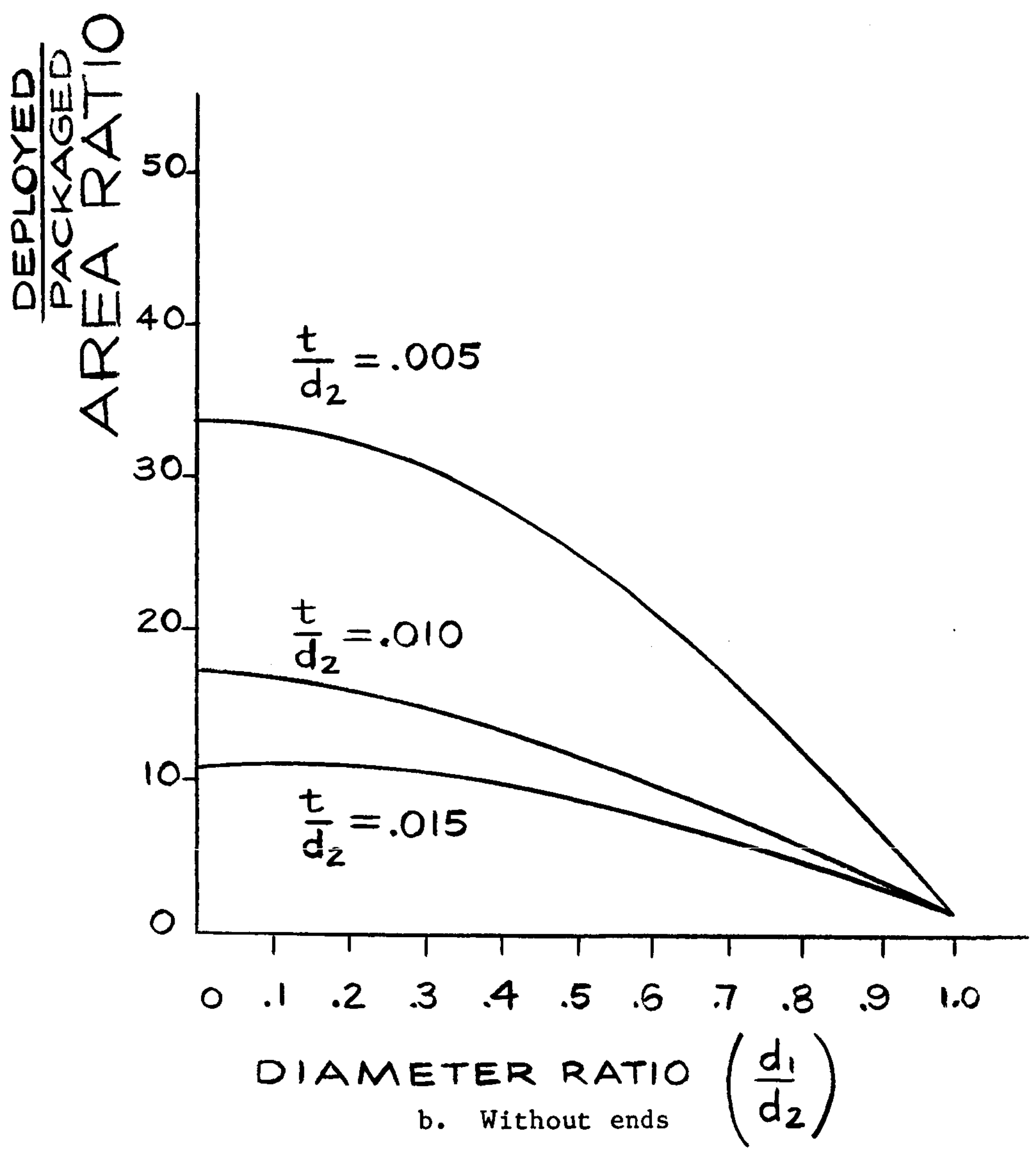
b. Without Ends

Figure 5-18b Radially-Expanding Cylinder Area Ratio



a. With Ends

Figure 5-19a Radially Expanding Cylinder Volume Ratio



b. Without ends

Figure 5-19b Radially Expanding Cylinder Volume Ratio

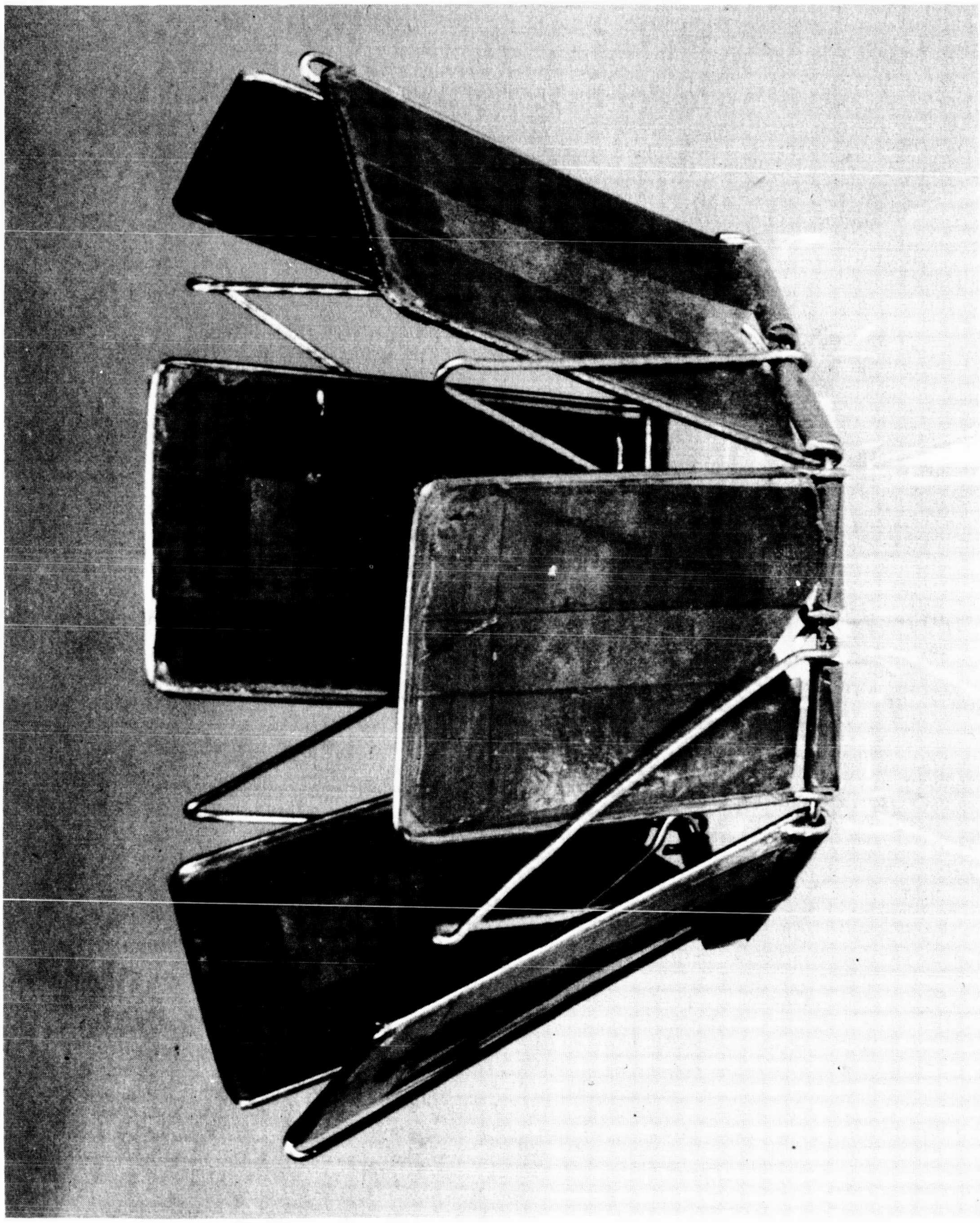


FIGURE 5-20 AXIALLY EXPANDED PANEL FRAME STRUCTURE

and the interlaced end-frames are folded inward, thus forming a compact payload with a polygon cross section. Upon deployment the panels move radially outward to increase the diameter of the cylindrical shape. Figure 5-17 shows the frame structure extended in an outward position. A more likely use would have the frame inwardly positioned, and as the outward longitudinal movement occurs the panels travel outward. The interlaced end-frames show the framework details (Fig. 5-17). This type of structure would be most useful for missions where expanded surface area is required.

When the structure is in its final deployed configuration, knee braces connecting the framework to the panels should be provided.

SECTION VI

PANEL-SPHERE

6.1 INTRODUCTION

This section describes another variable geometry (VG) design concept in which a sphere is developed from a set of panels. A deployed panel sphere is shown in Figure 6-1. The deployed structure has a grid system and the region between adjacent parallels and meridians locates a panel.

This concept was developed to satisfy the requirement for a rigid structure capable of being expanded to a near-spherical shape. The design accomplishes this and can be constructed to provide

a. favorable weight-strength ratio

b. micro-meteoroid resistant structure, and

c. small, compact launch package with high expansion ratio

6.2 PANEL TYPE ENCLOSED SPHERE

6.2.1 SYSTEM DESCRIPTION. The established grid system for the surface of the basic sphere is similar to the geodetic system used for the surface of the earth. The intersection of planes normal to the sphere axis with its surface, are called parallels and the inter-section

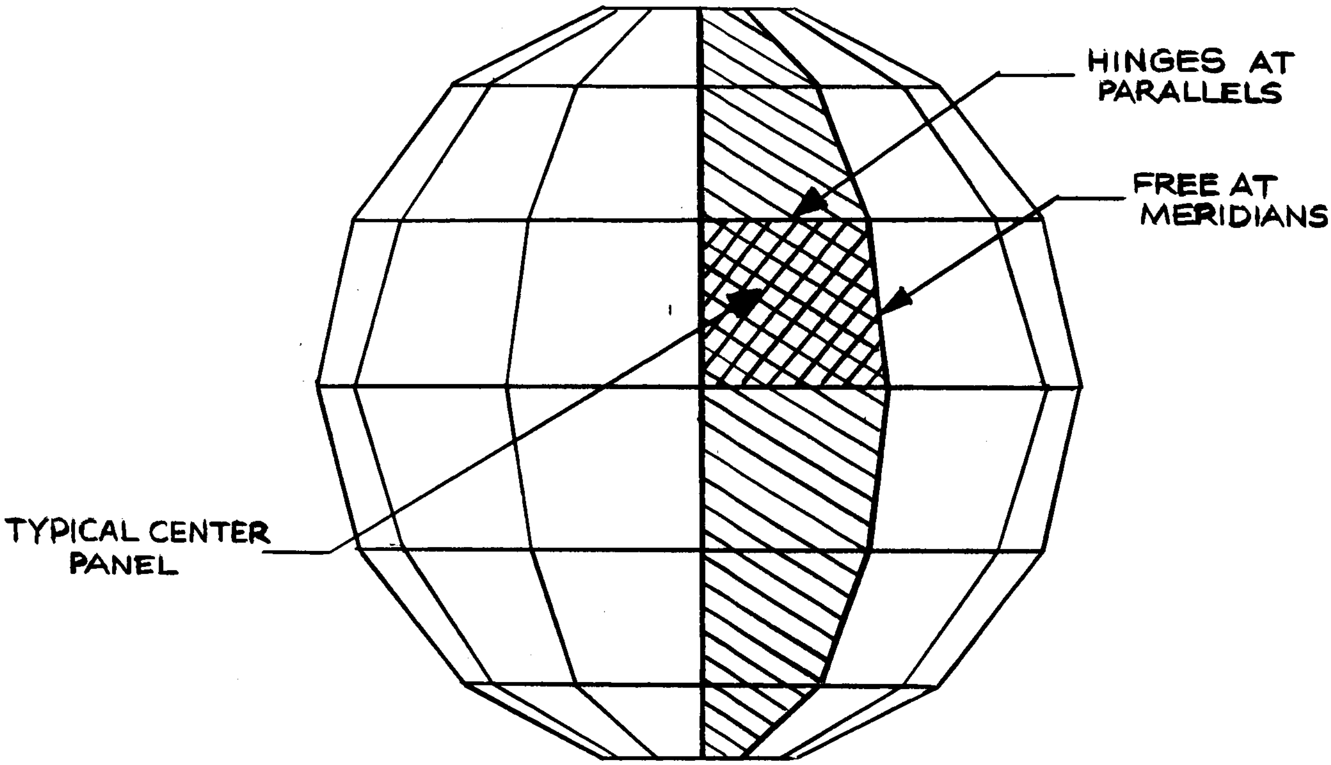


FIGURE 6-1 DEPLOYED PANEL SPHERE

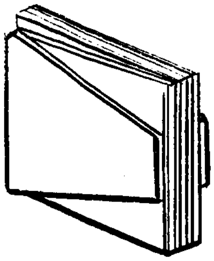
of planes passing through the sphere axis with its surface, are called meridians. The segments are made up of flat panels which are hinged at the parallels and free at the meridian lines.

Each segment of the sphere is compacted by folding as shown in Figure 6-2. The initial package includes a compiled array of these segments as shown in Figure 6-3 and the required actuation and deployment devices.

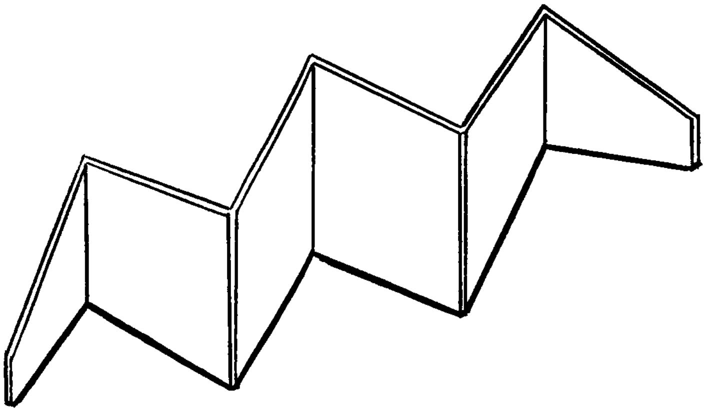
The panels are bounded by a load-carrying framework on their respective edges. Small cables pass through the segments along all parallels to facilitate erection and later to function as hoop-tension ties in the finished structure, (see Figures 6-3 and 6-4). The only additional erecting mechanism consists of the flexible hose shown in Figure 6-4 which is securely attached to each segment along its parallel in the equatorial plane. This hose is folded into the launch package and provided with a cold gas supply to inflate the hose and actuate winches which purse the cables when the sphere is erected.

6.2.2 DEPLOYMENT

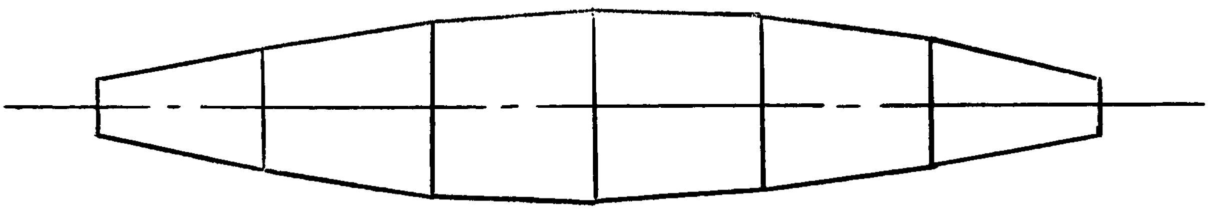
In the opening process, the hose is pressurized and the launch package is opened into a ring with the individual packages of meridional panels spaced uniformly around the circumference; a segment of this ring is shown in Figure 6-4. After the hose has been inflated and the segments properly disposed about the equatorial plane, precompressed torque springs are used to unfold the meridional segments.



A. FOLDED SEGMENT



B. PARTIALLY FOLDED SEGMENT



C. DEVELOPED SEGMENT

FIGURE 6-2 PANEL SPHERE SEGMENT

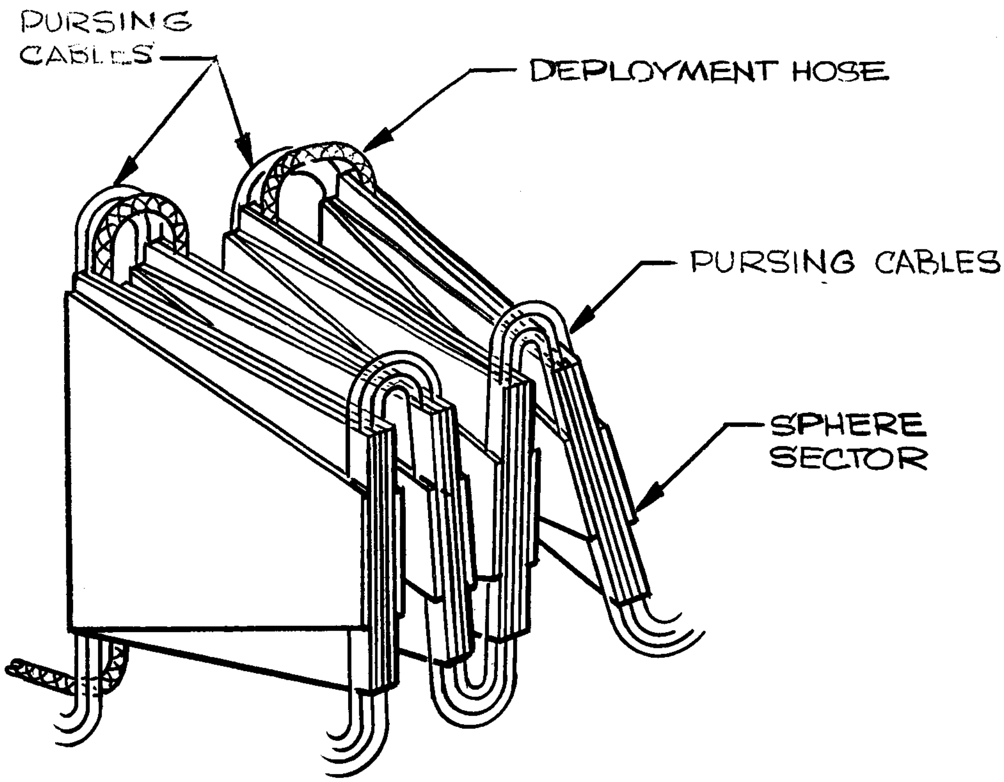


FIGURE 6-3 SEGMENTS OF PANEL-SPHERE PACKAGE

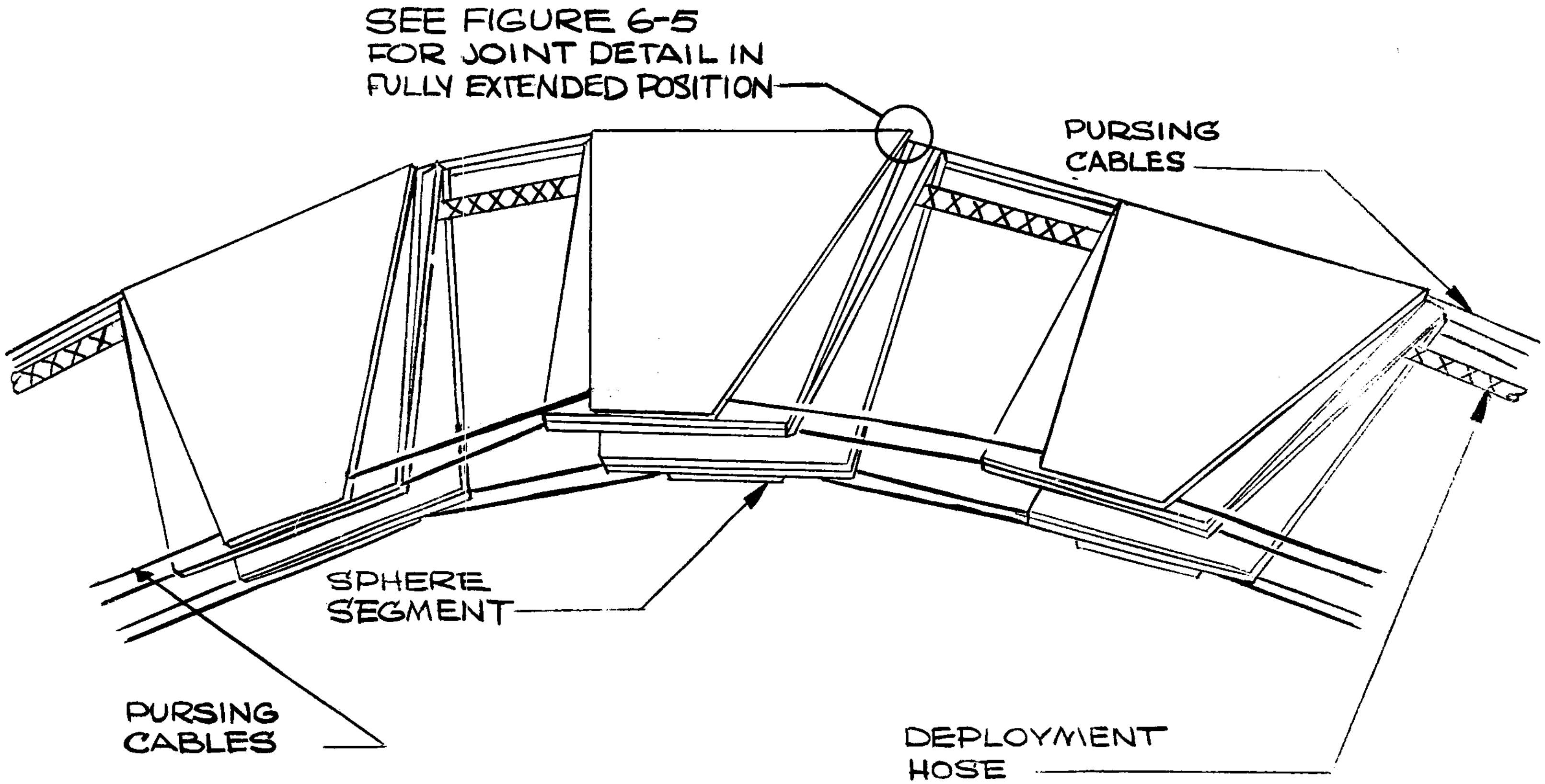


FIGURE 6-4 DEPLOYMENT CIRCLE SEGMENT

All segments are then properly located and ready for pursing. A typical panel joint is shown in Figure 6-5. The pursing cables and joint spacing are shown before the pursing takes place. Cold gas winches, attached to the outside of each hinge are activated to pull the segments together.

6.2.3 SEALING TECHNIQUE

One possible sealing technique is the use of an elastomeric material. This could be performed in the following manner; prior to assembly, the mating meridional surfaces of all segments may be impregnated with an elastomeric material that cures to a dry flexible condition. The piano-type hinges at the parallels are similiarly processed before assembly. Polar cables are used to draw membranes over the openings at the poles and this completely encloses the sphere. Next a vaporized catalyst is released inside the sphere. Since the external enviroment is a vacuum this pressurized catalyst will seep out through the meridional butt joints and parallel hinges causing the necessary bonding which completely seals and rigidizes all joints and hinges. An alternate design might use a pressure bladder which can be inflated inside the structure after erection, thereby ensuring pressure containment.

6.2.4 SYSTEM EVALUATION

a. The final erected structure will posses a favorable weight-strength ratio if fabricated from fiberglass

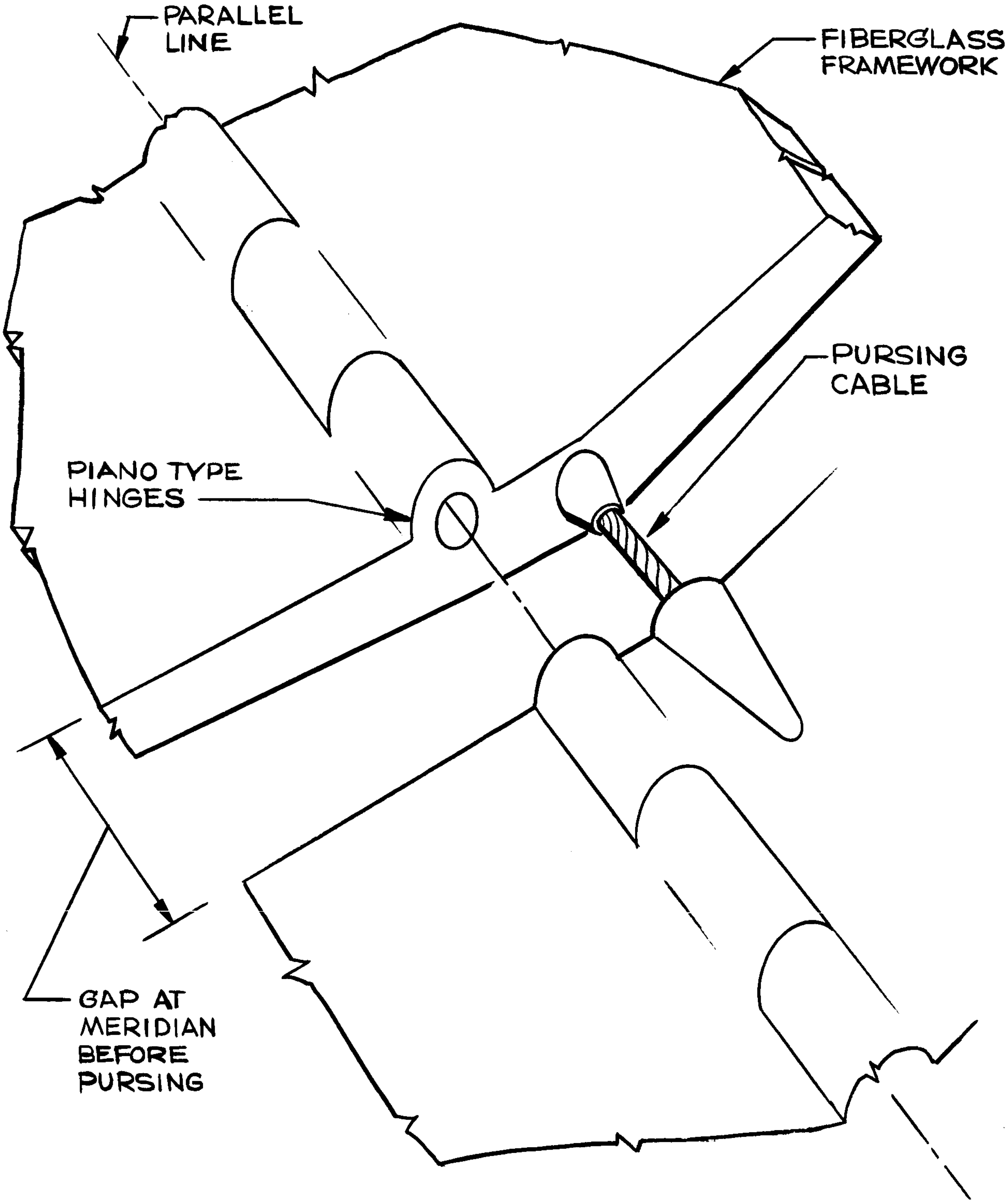


FIGURE 6-5 TYPICAL PARALLEL JOINT BEFORE FINAL CLOSING

honeycomb panels. These can, of course, be manufactured under ideal terrestrial prelaunch conditions. It may be possible that the sealing process outlined in Section 6.2.3 can be developed to make the panels capable of transferring shear across the meridional and parallel joints, thus transforming the entire surface into a monolith.

b. The system shown in Figure 6-1 consists of 12 segments each of which has seven cables and five hinges. Each of the seven cables may have its own gas operated pursing winch. The additional erecting mechanisms consists of a cold gas supply and a flexible deployment hose. At launch the cables are drawn as tightly together as possible without impairing the necessary freedom for launching and deployment. If this system is deployed in space, the deployment will take place in a zero "g" environment and the small force exerted by the pressure hose will be adequate. When the hose is fully inflated, the individual segment packages unfold by means of torque springs located at each hinge. All segments and panels are properly spaced and ready for pursing. The cold gas winches are then activated to pull the segments together and form the sphere. From a reliability standpoint the components and mechanisms appear to have simplicity and positive operational characteristics, but the process requires detailed development. Sealing is accomplished with the addition of a few simple parts. The over-all system can be made resistant to micro-meteoroid damage.

c. The twelve element sphere shown in Figure 6-1 can be contained in a launch package which has a square plan form if desired.

6.3 FRAMEWORK SPHERICAL SURFACE

6.3.1 SYSTEM DESCRIPTION

The framework spherical surface shown in Figures 6-6 and 6-7 has the same basic geometry as the panel-type enclosed-sphere of Section 6-2. The two systems differ only in the manner in which shear is carried through the individual panels.

6.4 AREA-VOLUME RELATIONSHIPS

The sphere can provide a substantial surface area and volume enlargement for a given space application. The panel sphere requires a package of panels, the size of which is determined by the panel thickness. Therefore, a substantially large launch package will result as the panel thickness is increased, with no apparent increase in the volume of the deployed sphere.

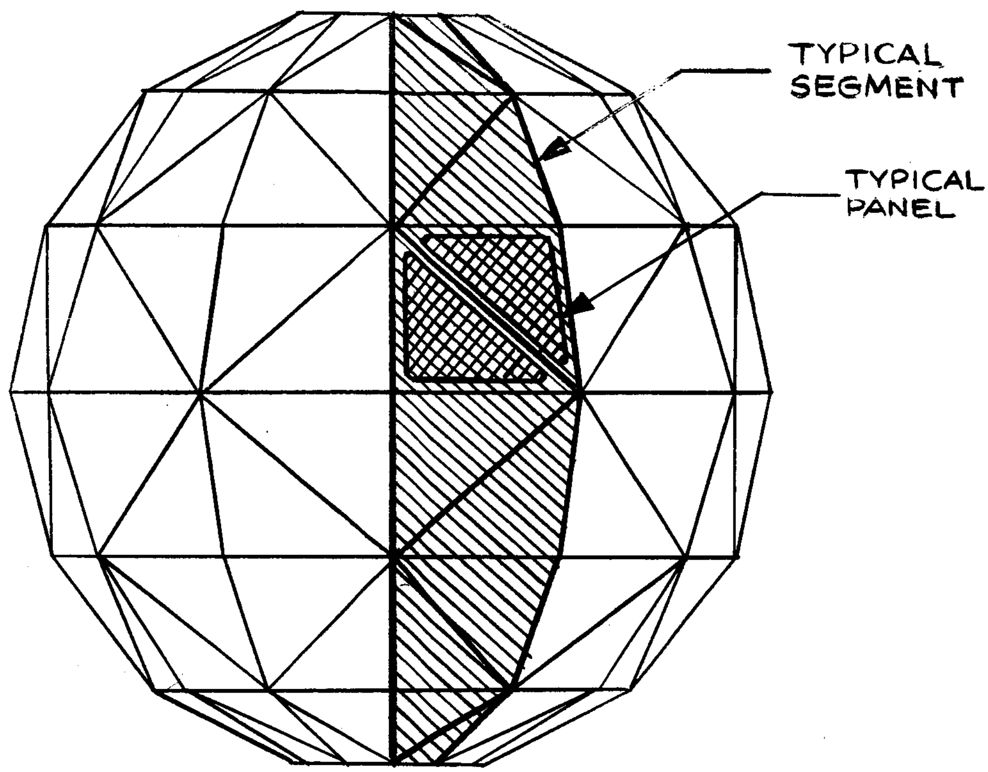


FIGURE 6-6 DEPLOYED FRAME-SPHERE

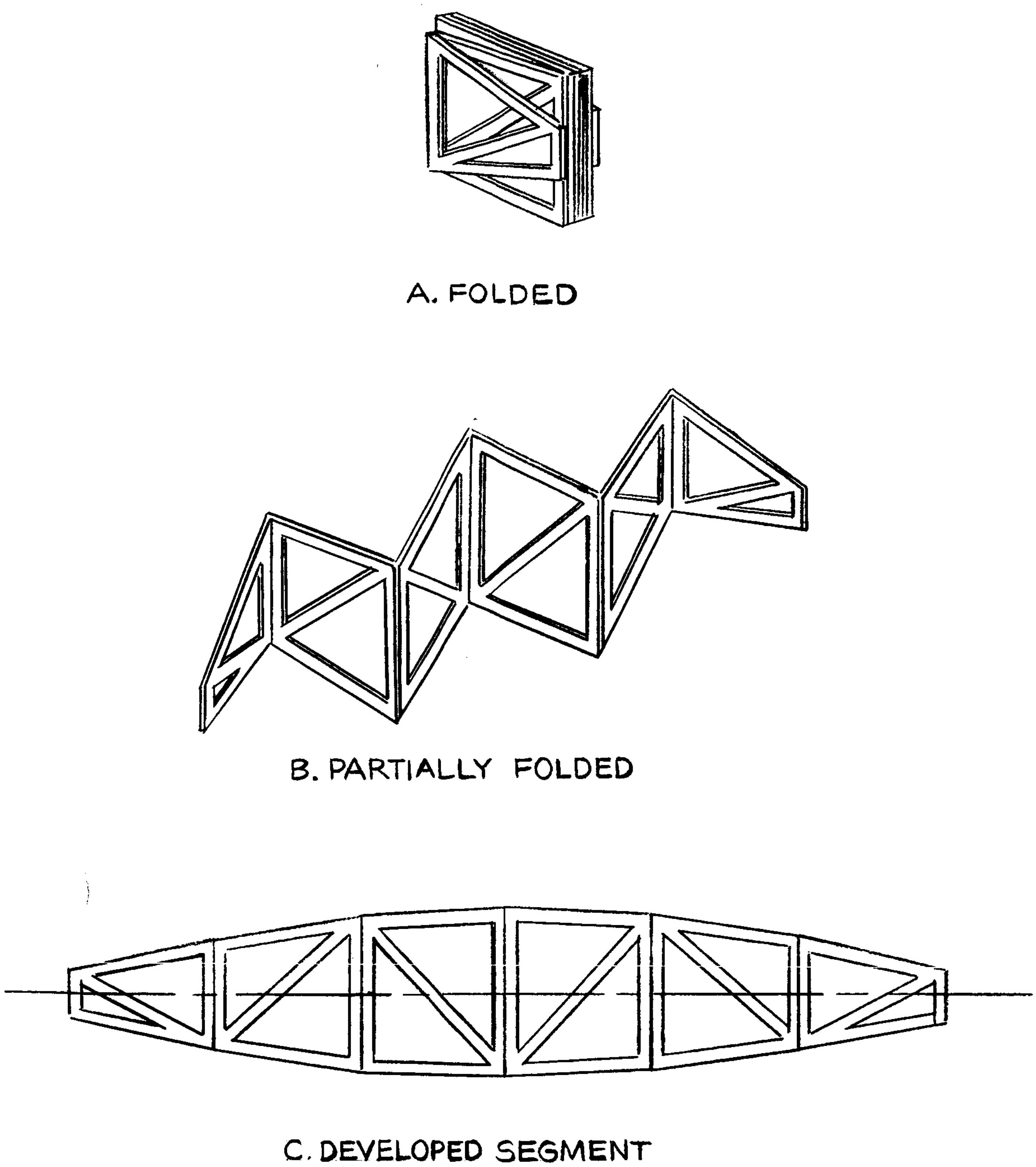


FIGURE 6-7 FRAME SPHERE SEGMENT

A study was made to determine the surface area and volume ratios which can be developed with this system. The initial package was assumed to be a cube with over-all dimension of d_2, (Fig. 2-2d); d_1 provides a measure of the volume allowed for storage of additional actuation and/or other equipment.

The study considered varying thickness ratios (t/d_2). The results are shown in Figures 6-8 and 6-9. It will be noted that substantial increases in area and volume are possible if the selected thickness ratios are small.

6.5 CONCLUSION

The panel sphere system (like the other rigid structures considered in this report) uses components which are terrestrially fabricated in their final state. This permits a structural system of known uniformity and capability of providing basic protection against micrometeoroid and radiation hazards.

The panel sphere concept provides a means to obtain a doubly curved surface in a deployed structure. This section has discussed the sphere but it appears possible that other singly or doubly curved structures can be developed by this same technique.

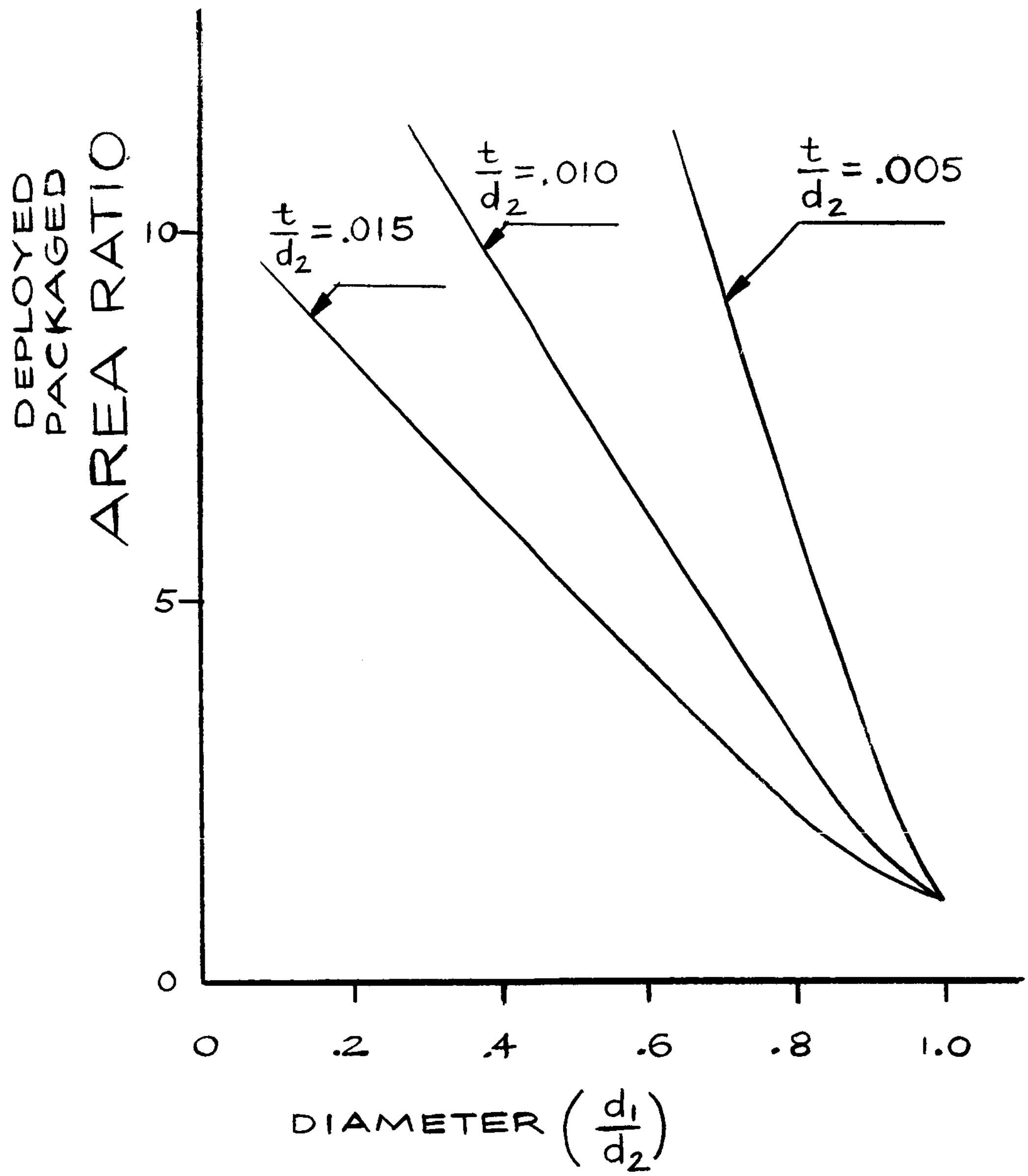


FIGURE 6-8 PANEL SPHERE AREA RATIO

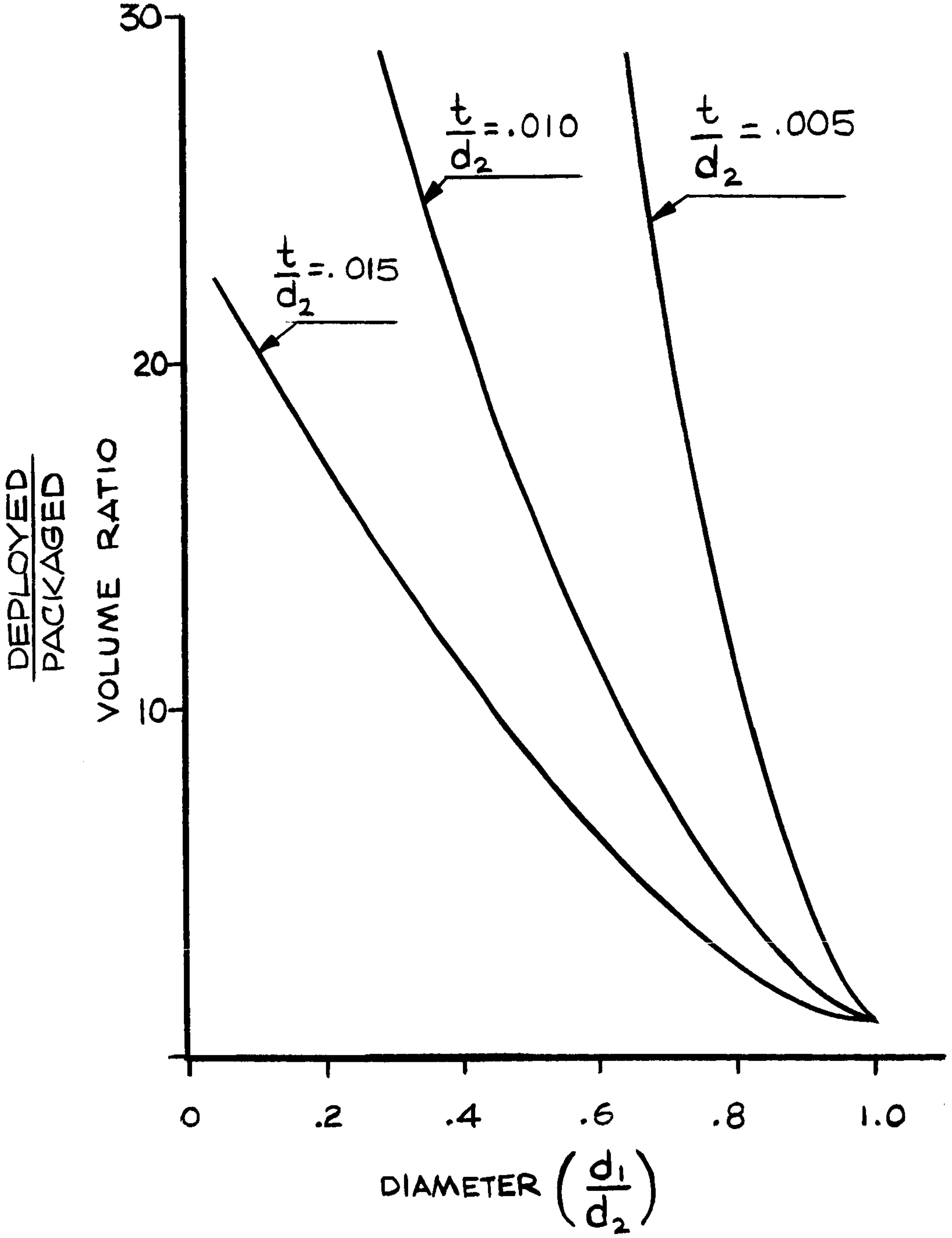


FIGURE 6-9 PANEL SPHERE VOLUME RATIO

SECTION VII

KINEMATIC CONSIDERATIONS

7.1 INTRODUCTION

The actual design of a VG structure will entail the establishment of a number of parameters for component selection which will influence the selection of the deployment techniques, locking in a deployed state and hinging of the moving parts.

This study has nominally investigated these areas for the purpose of establishing system feasibility. This section surveys the methods of attachment of components, the techniques of hinging, actuation, and locking. This section provides only a nominal investigation to establish general system feasibility and usefulness.

7.2 HINGES

The requirements for hinges in any VG structure will be determined by the geometry of the structure and by deployment and refolding capability. A number of hinging techniques are possible, such as:

a. conventional hinging (piano hinges)

b. flexible materials (fabric)

c. sleeves.

The conventional hinges which use multiple points of contact for rotation can be adapted to this application. Basically, the type of joint desired for deployment of the structure and the magnitude of the developed loads will determine the type and size of the hinge. The piano-type hinge may be used if the tight joint without any surface protrusion is desired. The standard door-type outer or inner hinges can be used when this is not a problem.

It may be desired to provide a flexible material, perhaps in the form of a fabric, as the hinging material. This would provide the rotational capability of the joint. However, this joint would not be capable of resisting shear-type loads.

Sleeve hinges, shown in Figure 7-1 provide a similar situation as the fabric hinge design. Here the rotational capability is present but limited shear resistance can be developed. This design would find its greatest application in the articulated-arch VG concept.

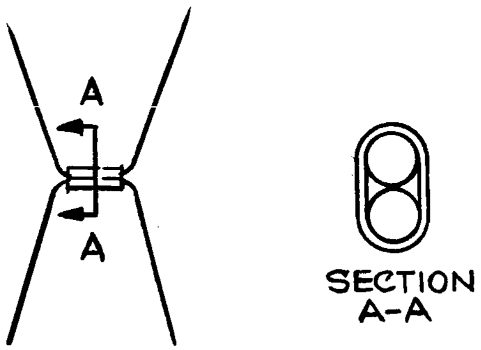


Figure 7-1. Sleeve hinge detail

7.3 ACTUATION DEVICES

The deployment of VG structures in space requires unfolding and possible refolding of the structural components. Hence, the actuation devices to accomplish this play an important part in establishing the feasibility of this system.

The deployment of the structural members to their proper position depends upon an expenditure of energy to move the frame mass from a folded condition to the developed position. A number of different energy sources are available. Which of these is the most desirable will depend upon a number of factors, some of which are discussed below. The energy sources can be broadly categorized as follows:

a. mechanical

b. chemical

c. electrical

d. manual

Some of the characteristics of each of these sources will be discussed below. The optimum energy device is a function of several parameters. Some of these are:

a. Application - The energy device will depend upon its function, the magnitudes of energy required, the time for deployment, etc. Since these can vary with every system and structure, the best device should be selected for each application.

b. Weight-Energy Criterion - The best device would be one which would store substantial quantities of usable energy and have negligible weight. The device should be such that the energy can be readily harnessed.

c. Volumetric Limitations - The size of the component is important to obtain maximum packagability.

d. Reliability - A very high over-all system reliability is necessary, which implies that the reliability of an individual device be high. However, certain fail-safe features are necessary to accommodate situations where failure of one actuation device may jeopardize the entire deployment operation.

e. Disassembly Requirements - The VG structure may require a feature of ready disassembly and subsequent reassembly. In such a case, multiple actuation devices may be required or features which permit the replacement of the spent devices with new loaded ones. In some cases, electrical devices with directional control may be the desired system.

7.3.1 MECHANICAL ENERGY

The technique of utilizing mechanical energy for the deployment of VG components would probably be used. The methods of storing the mechanical energy fall into three broad categories: (a) by compressing or winding springs; (b) by using gas stored under pressure; and (c) utilizing the spin energy given the spacecraft during a latter boost stage.

7.3.1.1 Springs - There are two types of springs that may have application for rotary actuation: (a) the helical spring and (b) spring motors similar to the type used in cameras and clocks. The spring is precompressed and properly located during packaging of the structure. A release mechanism which can release the spring upon signal will be required. The spring actuator is more applicable to a unidirectional requirement. However, by properly locating two oppositely disposed springs, bidirectional requirements may be satisfied. The amount of energy which can be stored in a given spring is limited and extremely large quantities can not be generally stored in a single device. It appears, at least qualitatively, that the springs will be limited to nominally sized structures.

7.3.1.2 Compressed Gas - It is possible to design a pneumatic system whereby the energy stored within a compressed gas could be used to deploy elements of the VG structure. The compressed gas can be stored under high pressure and therefore possesses a substantial quantity of energy. It is possible to use this design by providing a piston head arrangement. The head could be attached to a gear arrangement or a shaft with a bearing in a helical race, thereby achieving arch rotation.

It appears that this scheme could deploy and refold the system. This can be accomplished by permitting either end of the cylinder to move under pressure. Techniques which permit the controlled release of the piston heads must be developed but should not present many problems.

Another technique which could be used is direction of the sun rays, by a solar collector, to a gas container which becomes heated, thereby expanding the gas, and moving the piston.

7.3.1.3 Centrifugal Forces - During the final stage of spacecraft launch, it is frequently spun to stabilize the vehicle to obtain greater accuracy during this orbital insertion. After orbit is achieved, the spacecraft rotation is slowed or stopped by deployment of masses from the spacecraft. The system energy developed by spinning can be used in deployment of the VG structure.

It appears that all VG systems cannot use this energy source. Those which appear to be most feasible are the radically expanding system.

7.3.2 ELECTRICAL ENERGY

Another way to develop the required actuation torque is use of an electric or servomotor. Some of the advantages of this type of actuation system are listed below:

a. It can be bidirectional (unfolding/refolding) to any intermediate configuration.

b. It is readily available as off-the-shelf hardware and would require minor detail design changes for adaptation to most systems.

A power source is required for this type of actuator. This, in general, will not be an extra item because most spacecraft will have a power source aboard for other functions. However, it may result in increased over-all power requirements for the system.

The required deployment torque can be achieved by using a speed reducer. This could develop a system with the least weight since the reducer could have a built-in self-locking device to lock the motor in any desired position and structural configuration.

7.3.3 CHEMICAL ENERGY

In this general category, one would consider those methods whereby a chemical reaction between two substances causes an energy release, such as the generation of a gas, or another substance with an increased volume whose expansion can be utilized to drive a piston or a drive shaft. A gasoline-driven engine can be considered in this category.

7.3.4 MANUAL ENERGY

There will be occasions where the deployment can be accomplished by a human being. In some instances it appears very possible that he could turn a crank and deploy the structure. There are limitations as to the amount of mass which he can move, but this will depend upon the system, gravitational forces, and the inherent friction. It appears that he would not be able to erect an extremely large system.

7.3.5 EXTENSIBLE TUBING

It is possible to use another system which is similar to the carpenter's steel tape which is rolled into a small package. In this case, a drum contains a sheet of metal which is rotated and feeds a guide and mandrel which forms the sheet into a tube (Ref. 19). This tube can be attached to the VG structure and cause its deployment. The system is shown schematically in Figure 7-2.

This system is not reversible and will result in the presence of tubing (not continuous) with the structure. Another disadvantage is the additional energy required to deform the sheet into a tube.

7.3.6 POWER OPERATED SPIDER

If the VG structure takes the form of an interlaced arch system, it will be possible to connect a drive mechanism to the arches at the point of overlapping. A gear-drive mechanism can be made a part of one strut. This mechanism mates with another interlaced strut. This system is shown schematically in Figure 7-3.

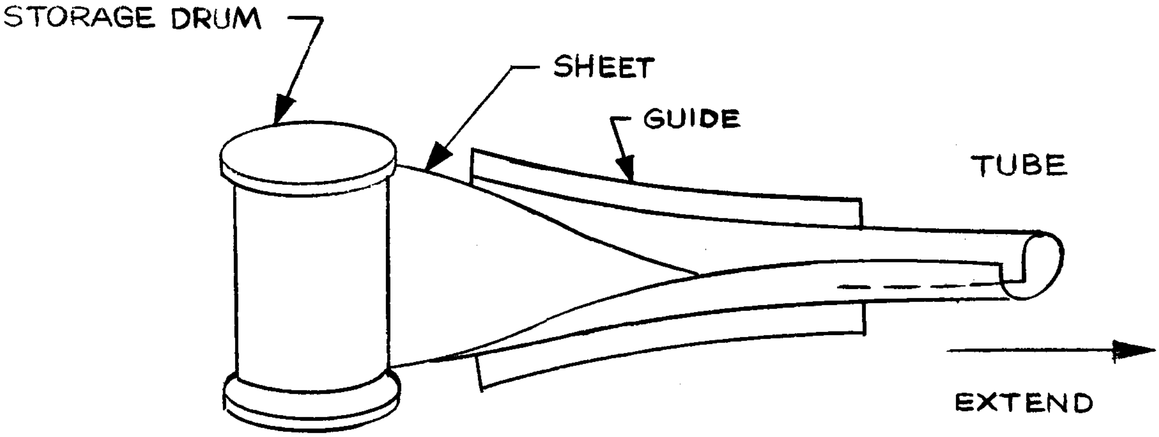
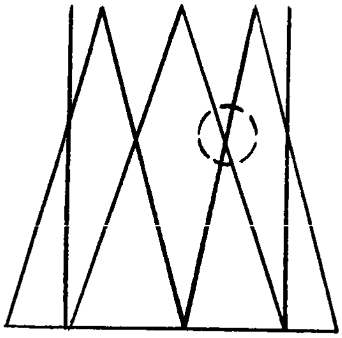


Figure 7-2 Extensible tubing



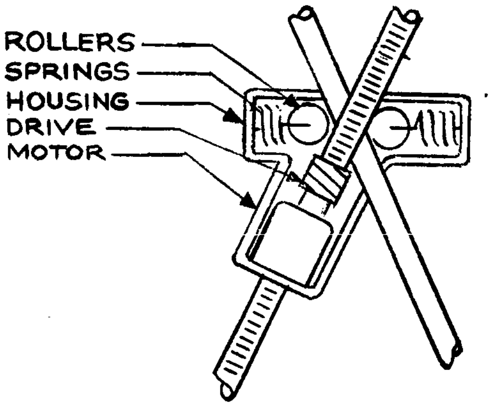


Figure 7-3 Power operated spider

7.3.7 SUMMARY

The relative merits of some actuation systems are shown in Table 7-1. The explosive system may be one of the better actuation techniques, if: (a) the inertia of the moving frames can be dissipated and (b) the frame does not have to be refolded.

TABLE 7-1

COMPARATIVE ACTUATION METHODS

Type	Available Energy	Bidirectional Capability	Relative Size	Controllability
Springs	Nominal	No	Large	With special design
Compressed gas	High	Yes	Nominal	With dual piston and gear arrangement
Electric motor	Must provide electrical energy source	Yes	Medium	Yes
Manual	Nominal	Yes	Large	Yes
Chemical	High	No	Small	Yes

7.4 LOCKING DEVICES

The locking device location will depend upon the structure used. In the case of the articulated arch system, it is necessary to provide locking at the intermediate developed ring to provide stability. This is true if the system is made up of one or more unit arch systems. This is shown schematically in Figure 7-4.

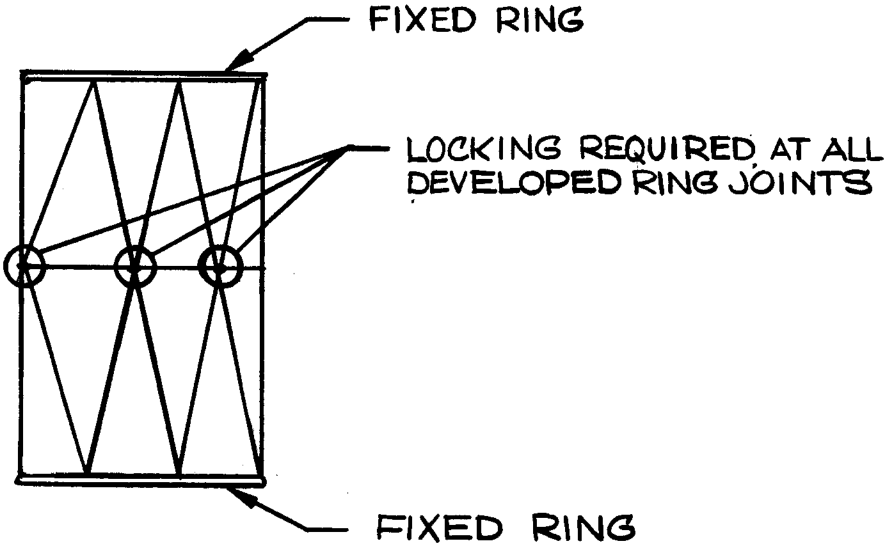


Figure 7-4. Deployed 2 stage articulated arch system

Locking devices may be required to hold the compressed structural array in place during launch, but they are absolutely necessary when the structure is deployed.

In the event that the actuation methods use spring locking devices, will be required to keep the springs compressed until assembly is desired. After the erection of the structure another system for locking is required.

It appears that two of the most common methods of locking can be employed: (a) a rachet mechanism which permits movement in one direction and (b) a displacement-locking device which engages or functions after an element passes a certain point in the travel of a component.

The locking device may have to be disassembled if the structure is to be disassembled. If this is done remotely a number of additional problems arise because all the locking devices must be released. This imposes more severe reliability problems to the system but can be readily accomplished.

SECTION VIII

CONSTRUCTION

8.1 INTRODUCTION

The variable gemetry (VG) structure in space will have to satisfy the requirements introduced by environment and mission function. Because the final system will incorporate many parts and subsystems, a multiplicity of materials will be used. It is conceivable that the final structural system will use metals, organic compounds, ceramics, glasses, etc. The hinge materials as well as sealing materials will also impose considerations. The following sections briefly introduce some important parameters of these disciplines.

8.2 MATERIALS

The behavior of materials in outer space is generally identical with behavior in an earth atmosphere. Some additional considerations arise from absence or presence of surrounding matter; i.e., vacuum and particles in space. (Refs. 20 and 21)

Some factors which govern material selection are:

(a) Electromagnetic shielding capability

(b) Meteoroid protection capability

(c) Structural properties and then retention

(d) Ease of fabrication

(e) Retention of pressure environment

(f) Minimal change in physical properties

(g) Cost

The following paragraphs consider the general material characteristics which are of importance in the VG design.

8.2.1 INORGANIC

Potential metallic structural materials for space missions are magnesium, aluminum, beryllium, titanium, steel, and their alloys. Difficult design problems are not anticipated for environmental conditions due to such factors as temperature, radiation, or vacuum sputtering. Evaporation is not expected to be serious with any of these metals under most circumstances. Special attention must be given to the operation temperature of magnesium to make sure permissible evaporation rates are not exceeded. Magnesium alloys are generally suitable for spacecraft life of less than one year. For longer lifetimes, magnesium should have a suitable evaporation barrier of gold, columbium, nickel, or other metal of lower evaporation rate.

In contrast, cratering and penetration damage are serious potential hazards, differing for each metal and structural usage. Design of a space structure which can survive micro meteoroid encounters must be made on a probability basis. For any selected survival probability and meteoroid characteristics of specified space environment, material selection can be based upon metal structural requirement. Design curves can be calculated for the thickness requirements. In summary, selection of metallic structural materials for space satellites is determined by space environmental factors for specific orbiting missions.

8.2.2 ORGANIC

Structural or reinforced plastics consist of a thermosetting resin binder and a woven or random fiber reinforcement in mat or laminated form. They are generally cured at a high temperature and pressure to a particular configuration. The high strength-to-weight ratio and relatively broad service temperature range suggests the increasing uses of these materials for space applications. The large variables such as fiber orientation provides the designer with almost unlimited combinations from which optimum materials can be selected for specific engineering requirements. Some possible VG applications of structural plastics would be fabrication of vehicle skins, stiffeners, supporting structures, and re-entry surfaces.

8.3 ENCLOSURE TECHNIQUES

8.3.1 POLYMER MEMBRANES, FILMS, AND FIBERS

Use of lightweight membrane and fabric structures has application in VG structures where bellows actuation or inflatable bags are needed. These types of materials are especially applicable for certain actuation systems and enclosures for housing life support systems.

The articulated arch VG structure provides a basic structural network which can develop any applied loads. Inasmuch as the resulting structure is open, its present basic form would be easily applied where structure is desired without containment of the enclosed volume.

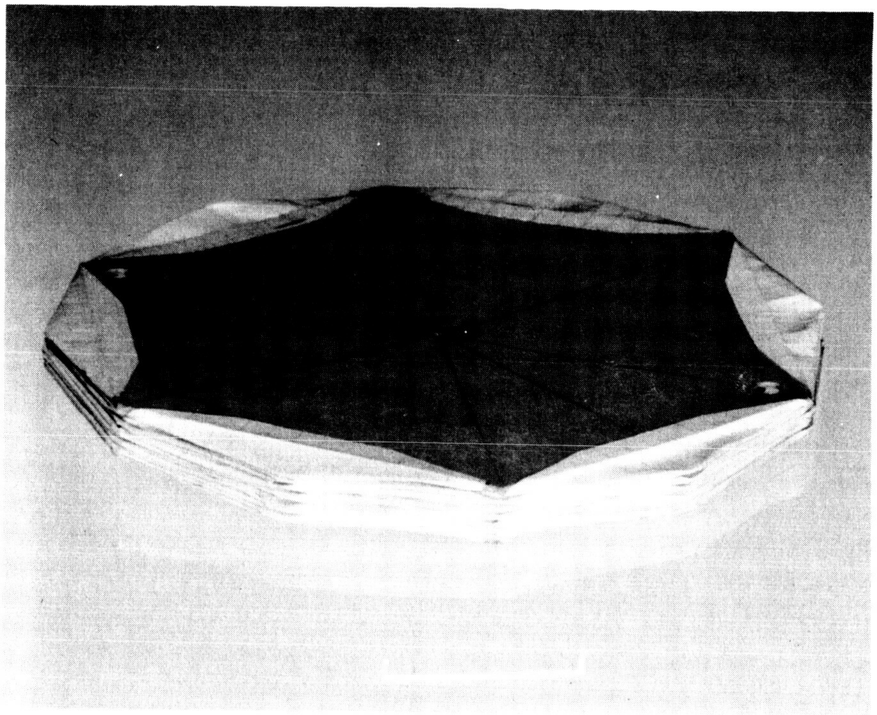
It appears that enclosure of the articulated arch system can be accommodated by the integrating enclosure methods with the rigid structure. The problem of greatest importance is the enclosure of the sides and will be primarily discussed here. The length increases from the compacted package to an enlarged configuration. Several possible techniques of covering the sides are considered here.

8.3.2 ACCORDIAN PLEATS

Complete encousure can be obtained by providing a stretchable fabric which expands axially. This concept can be applied with fabric which grows and encloses the system. Another version would use an expandable type which takes the form of a set of accordian pleats similar to that shown in Figure 8-1.

The fabric can be a similar material to that which is used in inflatable structures. This material has a substantial expansion ratio and could be readily used in a system of this type.

The use of the accordian pleat provides a means of enclosing a volume. In general, this design permits growth in one direction, and that a biaxial capability cannot be readily accommodated; a standard accordian



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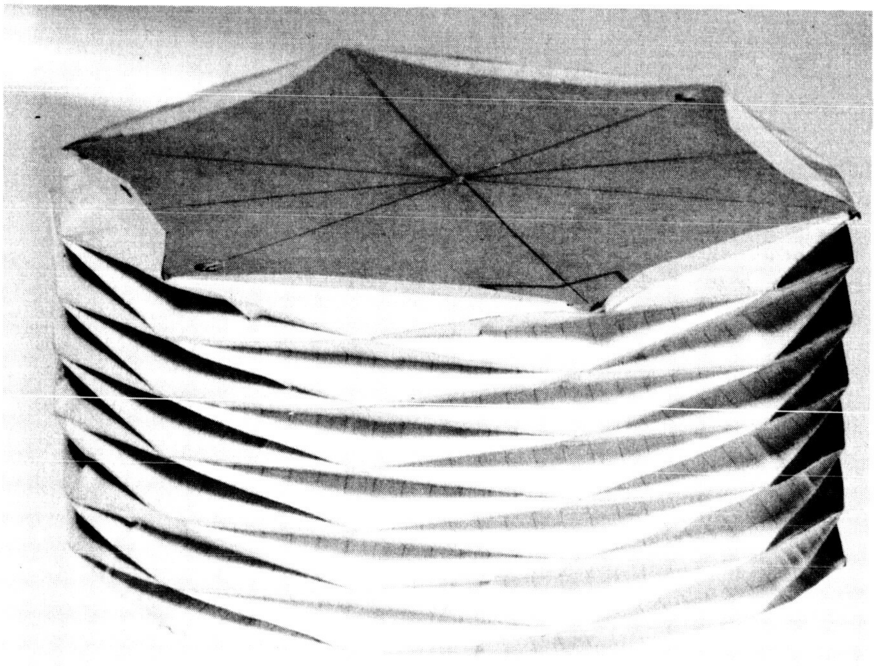

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FIGURE 8-1 ACCORDIAN PLEATED ENCLOSURE

fold is shown schematically in Figure 8-2a. The folding of the pleats can present some specialized problems but this can be readily accommodated by providing special folds at the corners. Two corner folds (f_1, f_2) see Figure 8-2a are required to make each pleat; one (f_1) being coincident with and in the same direction as the extended-position corner fold. This technique, however, may not be feasible for a large number of sides (greater than 10 or 12) because the angle between these folds may become too small for proper self-controlled folding.

Figures 8-2a, b, and c, illustrate variations of a second folding technique. Here, laterally-adjacent pleats are folded alternately outward (Fig. 8-2b), or semi-outward and semi-inward (Fig. 8-2c). Although this approach reduces the number of creases required in the folded position, an additional crease (f_1) is necessary to define the corner of the polygon in the extend position. The presence and fold direction of this corner fold is such that re-fold capability may be significantly impaired. A special case of this technique, however, appears promising for application to many-sided polygons. When the length of a fold line (f_2 in Fig. 8-2c) is selected as the length of a side of the polygon, a diamond-pattern accordion fold resultd as shown in Figure 8-2a. The required depth of fold, d, bears the following relationship to the number (N) and length (L) of sides of the polygon.

$$d = L \sin \frac{\pi}{N} \quad \text{(N even)}$$

This relationship, plus material elasticity requirements between the folded and extended positions, indicates that large N are most efficient.

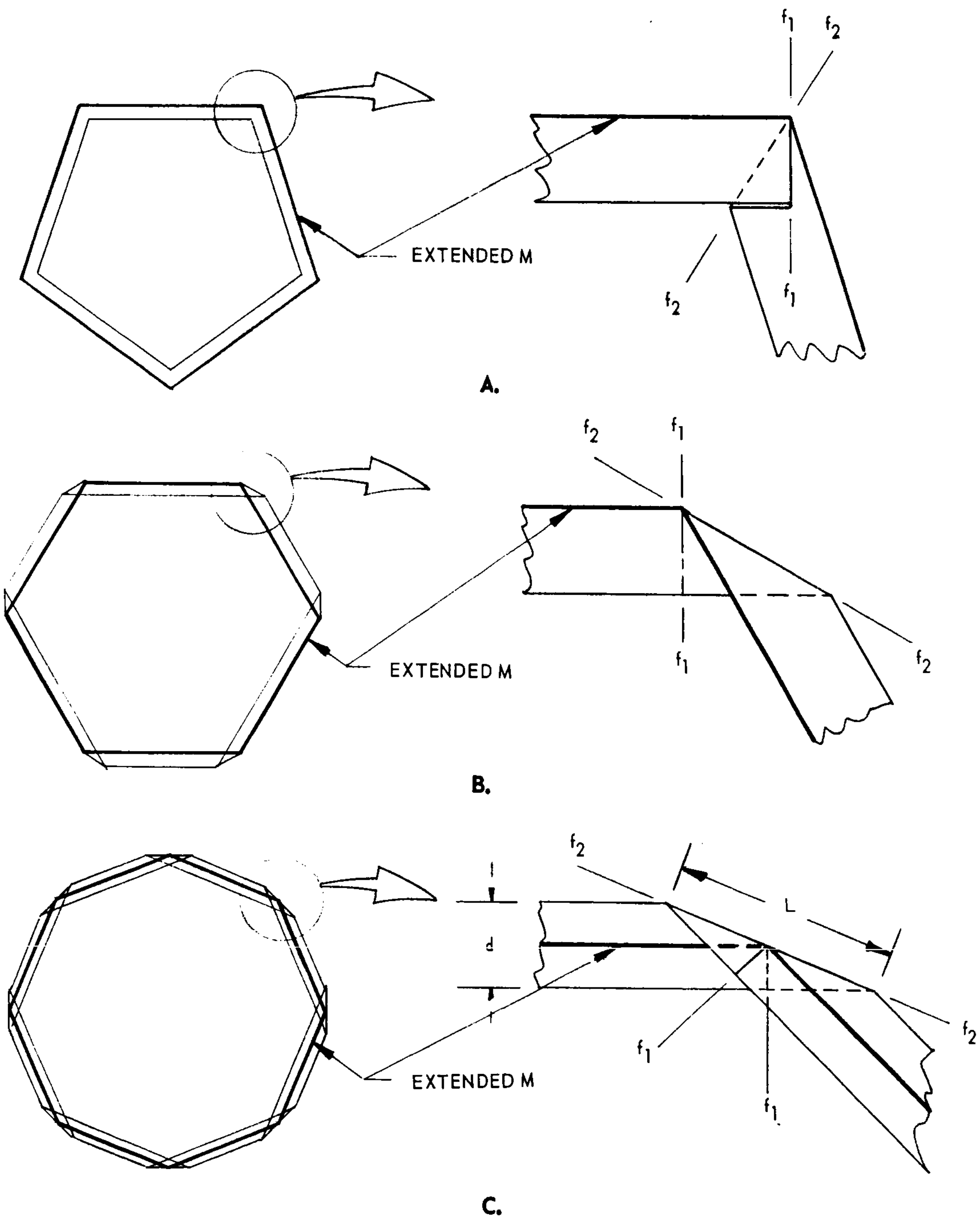


FIGURE 8-2 CORNER-FOLD PATTERNS

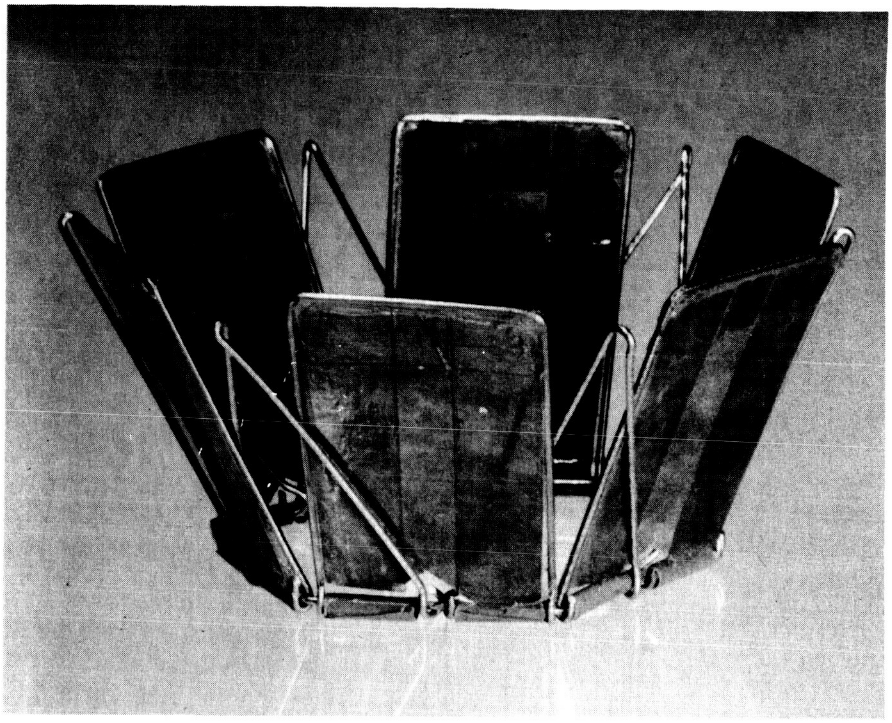
The d/L ratio, however, is also significant. The net result seems to indicate the most feasible N should be in the range of 10 to 20. As this approach does not require additional corner folds, re-fold capability should be excellent.

8.3.3 LONGITUDINALLY ORIENTED CONVOLUTES

Longitudinally oriented convolutes, on the other hand, could be mounted directly to the arches as well as to the supporting ring. The depth of the convolutes at the ring would be zero (fixed diameter ring) and increase gradually to maximum depth at the arch vertex plane. Thus, the convolute skin could be made to flex and conform to the over-all framework configuration as it opens and closes from cylinder to cone to disc and back again. As with rigid panel enclosures, convolute skins could conceivably be made in two or more layers to provide effective meteroid penetrating shielding, to incorporate self-sealing techniques, and to provide pressurization fail-safe capability.

8.3.4 PANEL-FRAME SYSTEMS

Another approach is aimed at providing extensible and/or re-foldable rigid panel enclosures. This cannot be accomplished with standard interlaced-arch systems due to panel interference and intersecting plane considerations. Figures 8-3a and b, however, show that certain framework variations can be successfully employed to provide rigid panel enclosures. These arch configurations are shown intermixed on the same base ring, with



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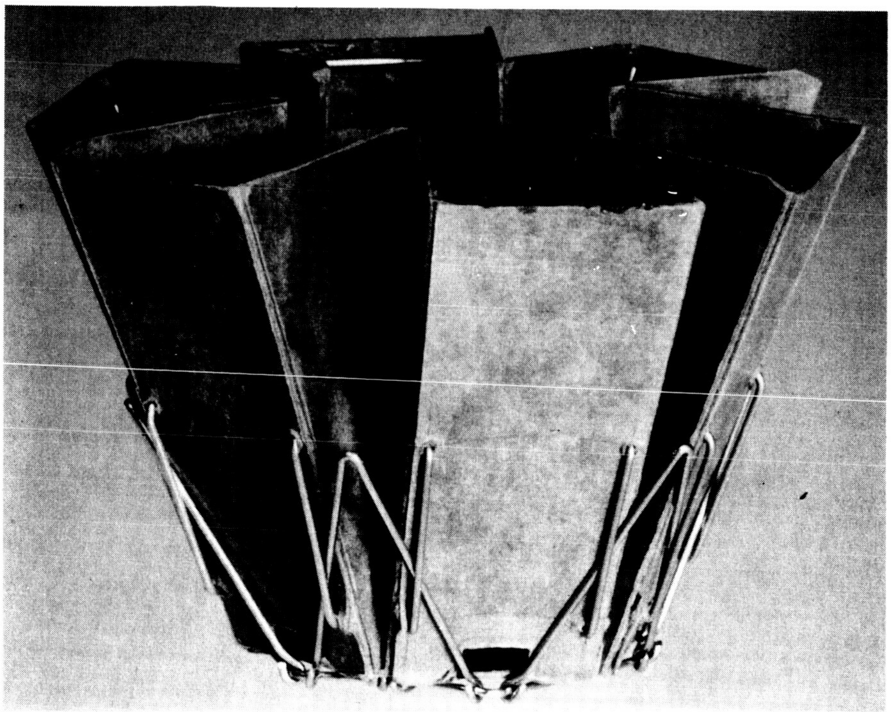

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FIGURE 8-3 PANEL-FRAME SYSTEMS

alternate paneled and actuator arches of different configurations and different hinge-line locations. Figure 8-3a shows a basic system satisfying the kinematic requirements of panels and interlaced frameworks. Figure 8-3b is a more complex approach wherein the triangular voids are filled with auxiliary panels. In this example, the interaction capability provided by the triangular arches is maintained by the addition of slide bars mounted near the edges of the rectangular panels.

8.4 SEALS

Sealing joints to prevent loss of pressure to the space environment vacuum can be effected during assembly and prior to launch. Flexible sealant materials will be selected from typical materials such as butyl rubber, fluorelastomers such as Kel-F, and polyethylene resins and films. The ultimate selection of materials for a specific space mission can be guided with the results of Reference 21, "Research on Elastomeric and Compliant Materials for Aerospace Sealants", which includes experiments on the effects of environment and radiation on sealants. Vacuum and radiation stability will be weighed against permeability in the final selection.

The unique joint sealing requirements of this study makes no new demands in the material field, but will require the development of new processes and fabrication methods. Examples would be development of bonding and mechanical fastening processes for flexible rubberized fabrics, establishment of the important material characteristics, and process techniques for inflatable seals and bags.

The sealing concepts which show promise for this application are:(a) strip and inflatable seals, and (b) continuous bladder seals.

8.4.1 STRIP AND INFLATABLE SEALS

All hinged seams can be sealed internally with adhesive materials, such as RTV 90 silicons or room temperature vulcanizing butyl rubber, employed to join the sealant to the inner neoprene surface. To obtain greater reliability, these sealants can also be fastened mechanically. Hence, the approach to sealing hinged seams appears to be sound. Minor problems exist, resulting from absorption of ultraviolet radiation, which will probably require a thin protective metallic coating such as aluminum on the sealants to minimize degradation of the polymetric sealants.

In a panel configuration, the self-sealing materials can be shielded from the relatively low level irradiation anticipated for an orbit below 500 miles (with the exception of unpredictable solar flares) by the outer sandwich structure. The variable of importance in this design is the temperature of the self-sealing composite materials. This can be accommodated by appropriate external thermal control coatings and by providing or developing a suitable bonding process for the structural sandwich.

8.4.2 CONTINUOUS BLADDER SEALS

A more positive method of sealing is to inflate a pressure-tight bag after the structure has been expanded and thus eliminate the possibility of leakage at seal intersections or overlaps. One possible design would be a bag fabricated with expansion convolutions and bonded to the inner walls of the structure. This method will require rub-strips over rough surfaces and the use of corner filling materials in deep recesses for bag protection, but a positive seal is assured even under such adverse conditions as docking operations, coupling, and thermal expansion and contraction.

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APPENDIX A

WEIGHT - STRENGTH STUDY

The equations used in the weight strength study are derived from this appendix.

This study is primarily concerned with the instability of the struts making up the framework. The maximum load applied to a column member was determined by equating the axial buckling load to the local crippling load. In this manner failure would theoretically occur by a general buckling of the member and localized wrinkling or crippling.

The relationships are derived from Eulers' long column buckling equation.

$$P_{CR} = \frac{\pi^2 EKI}{\ell^2} \tag{A1}$$

where

P_{CR} = Euler column buckling load

E = modules of elasticity

K = plasticity factor

I = moment of inertia

ℓ = column length

or

$$\sigma_{CR} = \frac{\pi^2 EKI}{A\ell^2} \tag{A2}$$

where

σ_{CR} = Euler buckling stress

A = cross sectional area

If equation (A2) is squared and the terms rearranged, it can then be rewritten as

$$\sigma_{CR} = \sqrt{\frac{\pi^2 EKP_{CR}}{\ell^2} \left(\frac{I}{A^2}\right)} \qquad (A3)$$

In the case of a thin wall tubular member, the assumed strut geometry, it is possible to use

$$I = \frac{\pi d^3 t}{8}, \quad A = \pi dt \qquad (A4)$$

where

d = diameter of tube

t = wall thickness

Substituting for I and A in equation (A3) gives

$$\sigma_{CR} = \sqrt{\frac{\pi EKP_{CR}}{8\ell^2} \left(\frac{d}{t}\right)} \qquad (A5)$$

The relationships for the maximum uniform stress which will cause local instability of the tube wall can be evaluated from the equation.

$$\sigma_{CCR} = \frac{K_1 \sqrt{E^2 K}}{(d/_t)}$$

where K_1 = area factor.

Solving for $(d/_t)$ in equation (A6), and then substituting it into equation (A5) gives

$$\sigma_{CR} = \sqrt{\frac{\pi E K P_{CR}}{8\ell^2} \left(\frac{K_1 \; EK^{\frac{1}{2}}}{\sigma CCR} \right)} \tag{A7}$$

For general and local instability to occur at the same stress level requires

$$\sigma_{CR} = \sigma_{CCR} \tag{A8}$$

Substituting (A8) into (A7) and squaring both sides of the equation gives

$$(\sigma_{CR})^3 = \frac{\pi \; E^2 \; K^{3/2} \; K_1 \; P_{CR}}{8\ell^2}$$

or

$$\sigma_{CR} = \sqrt[3]{\frac{\pi E^2 \; K^{3/2} \; K_1 \; P_{CR}}{8\ell^2}} \tag{A9}$$

The weight equation for a given member can be obtained from

$$W_i = WA\ell \tag{A10}$$

which can be modified by introducing $A = \frac{P_{CR}}{\sigma_{CR}}$, into the equation from

from

$$W_i = W \frac{P_{CR}}{\sigma_{CR}} \ell \tag{A11}$$

Substituting σ_{CR} from (A9) gives

$$W_i = 2\omega \sqrt[3]{\frac{\dfrac{P_{CR}^2 \; \ell^5}{K^{3/2}}}{\pi \; E^2 \; K_1}} \qquad \text{(A12)}$$

The loading condition which is applied to a deployed VG structure has been studied. In Figures 4-15 and 4-18, the distribution of the resisting loads is shown for bending moment and axial load. The total weight for a single stage, which is internal in a multiple stage network, can be found from

$$W_{TOT} = \frac{2\omega}{\sqrt[3]{\pi E^2 K_1}} \; \frac{N}{2} \left[\frac{\sqrt[3]{(2P_u)^2 \; L_u^5}}{K_u^{1/2}} + \frac{\sqrt[3]{(2P_L)^2 \; L_L^5}}{K_L^{1/2}} + \frac{4 \sqrt[3]{P_d^2 L_d^5}}{K_d^{1/2}} \right] \qquad \text{(A-13)}$$

The value for P_u, P_L, and P_d which is substituted into equation (A13) is the value corresponding to the highest loaded member in the category of an upper chord, lower chord, or diagonal member respectively.

The first term in the brackets represents the upper chord members and it is assumed that the load contribution from each stage is identical for the mutual members. The second term represents the lower chord member. The third term represents the diagonal members. If $L_u = L_L$, $K_u = K_L = 1$

and $P_u = P_L$, then equation (A13) becomes

$$W_{TOT} = \frac{2\omega}{\sqrt[3]{\pi E^2 K_1}} \; \frac{N}{2} \; \frac{2\sqrt[3]{(2P_u)^2 \; L_u^5} + 4\sqrt[3]{P_d^2 \; L_d^5}}{} \qquad \text{(A14)}$$

Rearranging terms it is possible to rewrite (A14) as

$$\frac{\omega_{TOT} \; h}{CM^{2/3}} = N\left(\frac{R}{h}\right)^{5/3} \left\{ \gamma + \beta \left[\alpha_d + \left(\frac{h}{R}\right)^2 \right]^{7/6} \right\} \qquad \text{(A15)}$$

where

$\gamma = 2U_u^{2/3} \; \alpha_u^{5/3}$, $\beta = 2.52 \; \Delta_d^{2/3}$

α_u = length coefficient for the upper chord member

α_d = length coefficient for the diagonal

U_u = load coefficient for upper chord member with the highest load

U_d = load coefficient for diagonal member with the highest load

$C = \dfrac{\omega(4)^{1/3}}{\sqrt[3]{\pi E^2 K_1}}$

It is possible to obtain the minimum point of the curve represented by this equation by $\dfrac{\partial\left(\omega_{TOT}/h\right)}{\partial (R/h)} = 0$. However, the resulting equation is complex since it is to a fractional power, and it is simpler to plot the curves and obtain the minimum points.

Appendix B
Area-Volume Relationships

The equations to determine the area and volume ratios for the various VG concepts are presented here. The systems analyzed were: 1) polygon disc, 2) strips, 3) telescoping cylinder or axially expanding variable geometry frame structure, 4) radially expanding cylinders, and 5) the panel sphere.

B-1. POLYGON DISC

The polygon disc is a design where a VG system is compacted by folding into a right cylinder. In its deployed state, the sides of the cylinder move outwardly and a near circular disk is formed. The area which is developed after deployment can be found as follows:

$$A_e = \frac{\pi}{4}\left(d + \frac{2h}{\sin\phi}\right)^2 \qquad (B1)$$

or

$$\frac{A_e}{\frac{\pi d^2}{4}} = \left[1 + \frac{4h}{d}\left(\frac{1}{\sin\phi}\right) + \left(\frac{h}{d}\right)^2 \frac{4}{\sin^2\phi}\right] \qquad (B2)$$

where the nomenclature is defined in Figure B-1

B-2. STRIPS

The VG structure known as strips provides a means by which a compact polygonal cylinder is used to provide surface area development. It is assumed that the base structure is a polygon, shown schematically in Figure B-2.

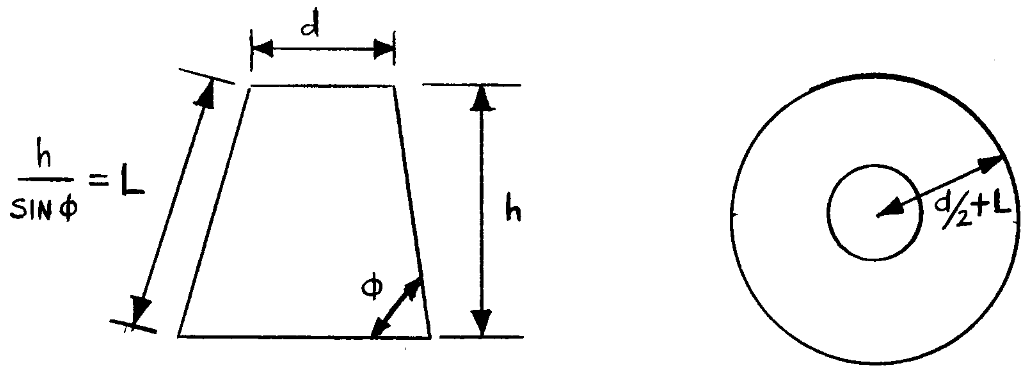

Figure B-1. Polygon disc - schematic

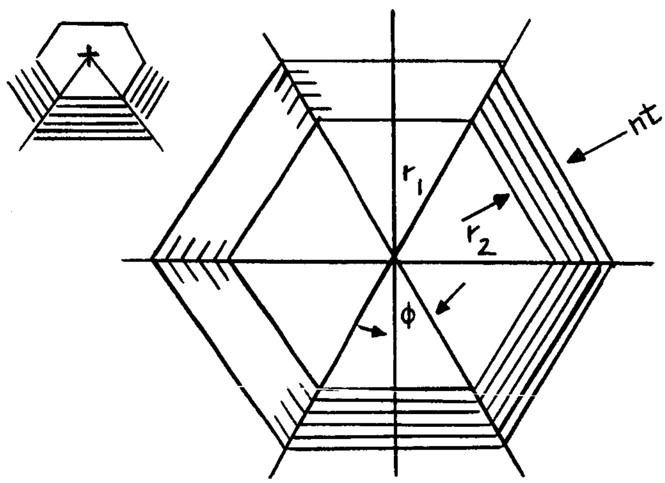

Figure B-2. Hexagonal strip

The average panel width for any polygon is

$$(r_1 + r_2) \sin\phi \tag{B3}$$

where

r_1 = radius of core assembly

r_2 = radius of compact assembly

ϕ = $\frac{180}{N}$ =

N = number of polygon sides

The expanded area (A_e) for a given side (both sides of the panel are considered effective) is given by

$$2 \text{ hn } N (r_1 + r_2) \sin\phi \tag{B4}$$

where

h = height of assembly

n = number of panels

By noting that $r_1 = r_2 - \frac{nt}{\cos\phi}$, substitute into Eq. B4 to obtain

$$A_e = 2 \text{ hn } N \left(2r_2 - \frac{nt}{\cos\phi}\right) = 2 \text{ hn } N \left(d_2 \sin\phi - nt \tan\phi\right) \tag{B5}$$

A nondimensional area relationship is

$$\frac{A_e}{hd_2} = 2 \text{ n } N \left[\sin\phi - \frac{nt}{d_2} \tan\phi\right] \tag{B6}$$

For purposes of an area-volume study, assume that the height (h) equals the compact core diameter (d_2) ; now

$$\frac{A_e}{{d_2}^2} = 2\ n\ N \left[\sin\phi \ - \frac{nt}{d_2} \ \tan\phi \right] \tag{B7}$$

The initial area (A_i) is taken as the circumferential area of the polygon (does not include the ends), that is

$$A_i = N{d_2}^2 \ \sin\phi \tag{B8}$$

The area ratio $\frac{A_e}{A_i}$ can be found to be

$$\frac{A_e}{A_i} = 2\ n \left[1 - \frac{nt}{d_2} \left(\frac{1}{\cos\phi} \right) \right] \tag{B9}$$

Noting that $n = \frac{r_2 - r_1}{t} \cos\phi = \frac{d_2 - d_1}{2t} \cos\phi$, substituting into (B9) gives

$$\frac{A_e}{A_i} = \frac{\cos}{2\ t/d_2} \left[1 - \left(\frac{d_1}{d_2} \right)^2 \right] \tag{B10}$$

The enclosed volume will not change from the original volume.

B-3. TELESCOPING CIRCULAR CYLINDER

The telescoping cylinder was also investigated parametrically to determine area and volume relationships. The telescoping cylinder was regarded as a right circular cylinder, each stage nested within the adjacent one and having the same length. It was assumed that the theoretical area and volume could be used; that is, no deviation was made for actuation volume. (See Figure B-3)

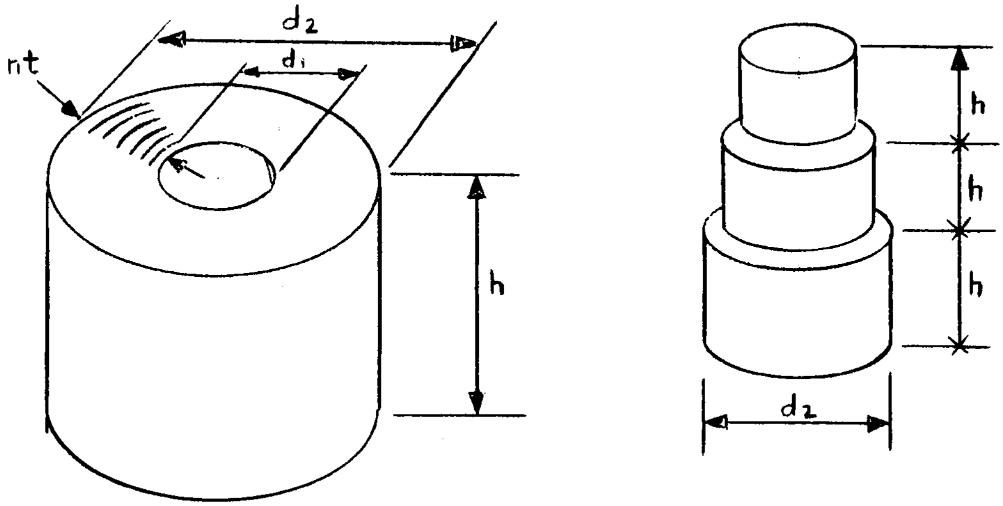

Figure B-3. Telescoping cylinder

Area Relationship

$$A_1 = 2\pi r_2 h$$

$$A_2 = 2\pi r_3 h = 2\pi(r_2 - t)h$$

$$A_n = 2\pi r_n h = 2\pi(r_2 - nt)h \tag{B11}$$

The total area is

$$A_{total} = 2\pi\left[r_2 + r_2 + r_2 + \quad t - 2t - 3t - 4t - nt\right]$$

$$= 2\pi\left[n\ r_2 - n\ (n-1)\ \frac{t}{2}\right]h \tag{B12}$$

This neglects the end arrays of the telescoping cylinders.

The number of stages (n) is defined as

$$\frac{d_2 - d_1}{2t} = \frac{1 - d_1/d_2}{2t/d_2} \tag{B13}$$

The expanded area can be found to be

$$A_e = h\pi\left(\frac{d_2}{t}\right)\left(1 - \frac{d_1}{d_2}\right)\left(\frac{d_2}{2}\right)\left[1 - \frac{1}{2}\left(1 - \frac{d_1}{d_2}\right) + \frac{t}{d_2}\right] \tag{B14}$$

The initial area $A_i = \pi d_2 h$ which can be used to determine the area ratio

$$\frac{A_e}{A_i} = \frac{1 - d_1/d_2}{d_1/d_2}\left(1 - \frac{1}{2}\left[1 - \frac{d_1}{d_2}\right] + \frac{t}{d_2}\right) \tag{B15}$$

Volume Relationship

The volume relationship can be determined similarly. The expanded volume can be found as

$$V_e = \frac{\pi}{4} h \left[n\, d_2^2 - 4\,(1 + 2\; 3 + \text{---} n) d_2 t + 4t^2\,(1^2 + 2^2 + 3^2 \text{---} n^2) \right] \quad \text{(B16)}$$

Rearranging and rewriting

$$V_e = \frac{\pi}{4} hn \left\{ 1 + 2\,(n + 1) \frac{t}{d_2} \left[\frac{1}{3} \left(\frac{t}{d_2}\right) \left(2n + 1\right) \quad - 1 \right] \right\} \quad \text{(B17)}$$

Substituting for

$$n = \frac{1 - {}^{d_1}/_{d_2}}{2\, {}^{t}/_{d_2}}$$

gives

$$V_e = \frac{\pi d_2^2}{4} h \left[\frac{1 - \frac{d_1}{d_2}}{2 {}^{t}/_{d_2}} \right] \left[1 + \left(1 - \frac{d_1}{d_2} + 2 \frac{t}{d_2}\right)\left(\frac{1}{3} \left[1 - \frac{d_1}{d_2} + \frac{t}{d_2}\right] - 1 \right) \right] \quad \text{(B18)}$$

Since the initial volume is

$$V_i = \frac{\pi\, d_2^2\, h}{4}$$

the volume ratio can be found as

$$\frac{V_e}{V_i} = \frac{1 - d_1/d_2}{2 - {}^{t}/_{d_2}} \left(1 + \left(1 - \frac{d_1}{d_2} + 2 \frac{t}{d_2}\right) \left[\frac{1}{3} \left(1 - \frac{d_1}{d_2} + \frac{t}{d_2}\right) - 1 \right] \right. \quad \text{(B19)}$$

B-4. RADIALLY EXPANDING CYLINDERS

The radially expanding cylinder also provides a means for extensive area and volume development. Three cases are considered here: 1) the expansion takes place by a frame structure integrally connected to a panel structural array, 2) all of the area developed is in the sides of the cylinder, and 3) the compacted volume of material goes into the sides and ends of the deployed cylinder.

B-4.1 CASE 1 - ACTUATED BY FRAMES

This case uses the integrated frame and panel structure. The expansion which can be achieved here is limited by the frame height (Fig. B-3).

It is assumed here that the maximum frame height is the height of the structure, and the front is connected to a base ring at either end of the configuration.

The area and volume can be found from consideration of the initial circumferential area $A_i = h \pi d_2$ and the final circumferential area (A_e) $h \pi (33d_2)$.

Since the diameter is increased by 3 three wall thicknesses must be provided in the initial area, that is,

$$d_1 = d_2 - 3t \tag{B20}$$

The initial volume is given as

$$V_i = \frac{\pi d_2^2}{4} h \tag{B21}$$

The final volume is given as

$$V_e = \frac{9 \pi d_2^2}{4} h \tag{B22}$$

Therefore from Eqs. (B21) and (B22) the maximum area ratio is

$$\frac{A_e}{A_i} = 3 \tag{B23}$$

and the volume ratio is

$$\frac{V_e}{V_i} = 9 \tag{b24}$$

B-4.2 CASE 2 - RADIALLY EXPANDING WITHOUT ENDS

The initial circumferential area (A_i) is πd_2^2 h and the initial volume (V_i) is $\frac{\pi d_2^2}{4}$ h.

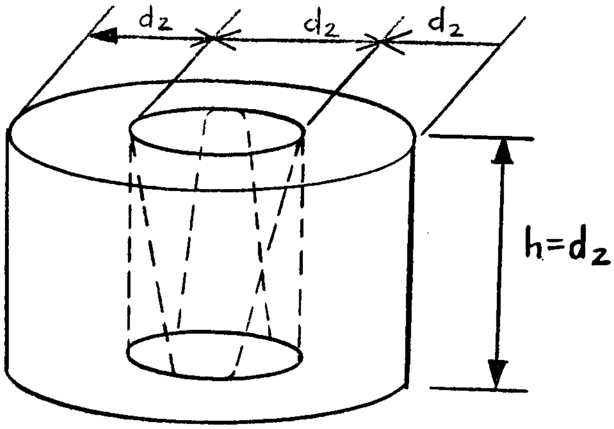

Figure B-4. Frame-actuated radially expanding cylinder

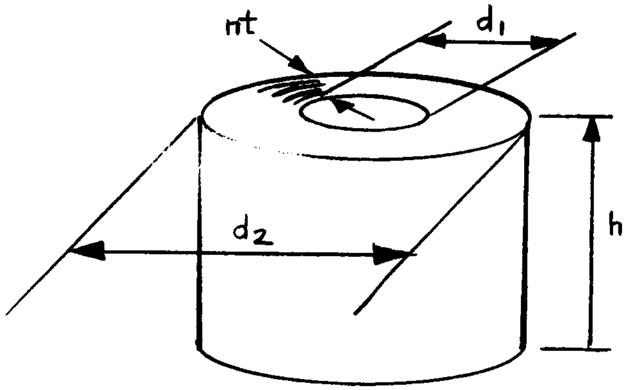

Figure B-5. Radially expanding cylinder without ends

If it is assumed that the area between the inner and outer diameters is completely filled with a material which can be used to cover the outside of the cylinder the volume of material available is

$$V_1 = \frac{\pi}{4}(d_1^2 - d_2^2)h \qquad \text{(B25)}$$

The material which would cover the outer circumference of a new cylinder with a diameter (D) has a thickness (t) then the volume of material required is πDht.

Equating (B25) to the deployed surface area gives:

$$\frac{d_2^2 - d_1^2}{4} = Dt \qquad \text{(B26)}$$

The new diameter

$$D = \frac{d_2^2 - d_1^2}{4t} \qquad \text{(B27)}$$

The area ratio is

$$\frac{A_e}{A_1} = \frac{1-\left(\frac{d_1}{d_2}\right)^2}{4\ t/d_2} \qquad \text{(B28)}$$

and the volume ratio

$$\frac{V_e}{V_i} = \frac{\left[1 - \left(\frac{d_1}{d_2}\right)^2\right]^2}{4\ t/d_2} \qquad \text{(B29)}$$

Case 3 - Radially Expanding With Ends

In this case the material filling the region between d_1 and d_2 goes onto the ends for covering as well as on the sides. The area and volume relationships for this case are given below:

Volume of material available $= \frac{\pi}{4}(d_2^{\,2} - d_1^{\,2})h$ (B30)

Expanded material volume $= Dht + \frac{2\ \ D^2 t}{4}$ for the particular case where

$h = d_2$, equate the above two equations to obtain

$$D^2 + 2Dd_2 - \frac{d_2}{2t}\ (d_1^{\,2} - d_2^{\,2}) \tag{B31}$$

Solving for $\frac{D}{d_2}$ gives

$$\frac{D}{d_2} = -1 + \left[1 + \frac{1 - \left(\frac{d_1}{d_2}\right)^2}{2\ t/d_2}\right]^{1/2} \tag{B32}$$

The surface areas can be found as

$$A_i = \frac{2\pi d_2^{\,2}}{4} + \pi d_2^2$$
$$A_e = \frac{\pi D^2}{2} + \pi D d_2 \tag{B33}$$

The surface area ratio is found to be

$$\frac{A_e}{A_i} = \frac{D^2 + 2Dd_2}{3d_2^{\,2}} = \frac{1}{3} \quad \left(\frac{D}{d_2}\right)^2 + 2\,\frac{D}{d_2} \tag{B34}$$

and $\frac{V_e}{V_i} = \frac{\frac{\pi D^2 d_2}{4}}{\frac{\pi}{4} d_2^{\,3}} = \left(\frac{D}{d_2}\right)^2$ (B35)

where $\frac{D}{d_2}$ is defined above in Eq. (32B)

5. The Panel - Sphere

The panel sphere concept is one which can achieve a rigidized spherical geometry.

The package used was arbitrarily selected inasmuch as the most ideal package configuration has not been evaluated. Therefore, it is assumed that the launch package (Fig. B-6) is a cube, d_2 on each side, but that a volume represented by a distance d_1 is present. This is a useable volume for actuation and/or other equipment.

The sphere is divided into equal size panel elements at the equator. The number of divisions around the equator is (n), through the poles (n).

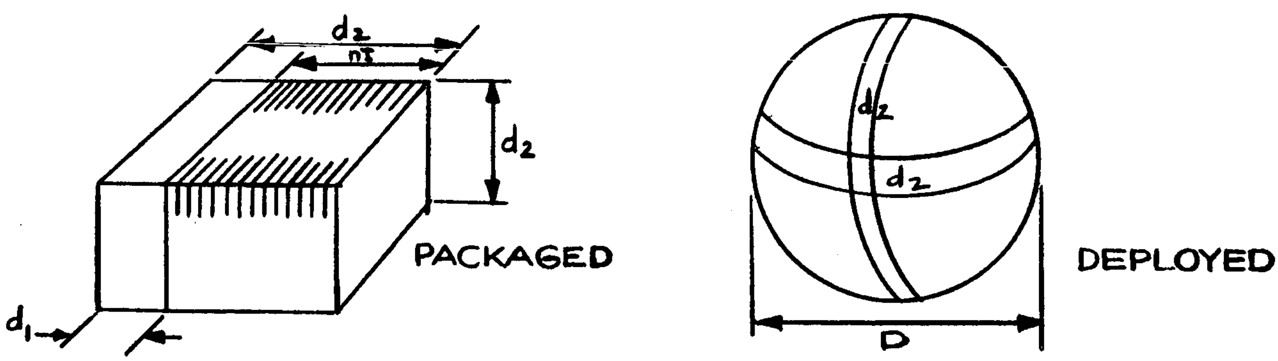

Figure B-6. PANEL SPHERE

The diameter of the deployed sphere is (D) and the dimension d_2 is found to be $d_2 = \frac{\pi D}{n}$

Volume of the initial package is $d_2^{\,3}$, the number of panels $\frac{n^2}{2}$

The volume of the deployed sphere is $\frac{\pi D^3}{6}$; the surface area πD^2

The area ratio $\frac{A_e}{A_i} = \frac{\pi D^2}{4{d_2}^2} = \frac{n^2}{4\pi}$ (B36)

and the volume ratio

$$\frac{V_e}{V_i} = \frac{\frac{\pi D^3}{6}}{{d_2}^3} = \frac{n^3}{6\pi^2} \tag{B37}$$

The value of n can be determined from

$$d_2 - d_1 = \frac{n^2 t}{2} \quad , \quad n^2 = 2\,\frac{1 - d_1/d_2}{t/d_2} \tag{B38}$$